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A ROLL, FIN, AND FIN CONTROLLER PREDICTION COMPUTER PROGRAM.(U)
JUN 80 S L BALES, J R TUCKER, G G COX
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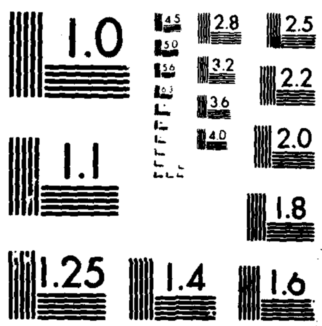

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A series of computer programs is under development for use in the design and evaluation of roll stabilization devices. This report is the user manual for the first program that has been completed. Identified by the acronym FINCON, the program is based on the work of Cox and Lloyd published in Volume 85 of the Transactions of the Society of Naval Architects and Marine Engineers. FINCON predicts stabilized and unstabilized ship roll motion,
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bilge keel and antiroll fin sizing effects, and the influence of fin controller characteristics by use of a one degree-of-freedom roll-motion equation. Nonlinear roll damping characteristics, derived from model experiments or by other means, are incorporated by a combination of equivalent linearization and an iteration procedure. Results are predicted for short-crested seas (for stabilizer design purposes) and long-crested seas, which are described by two-parameter Bretschnieder wave spectra.

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ABSTRACT

A series of computer programs is under development for use in the design and evaluation of roll stabilization devices. This report is the user manual for the first program that has been completed. Identified by the acronym FINCON, the program is based on the work of Cox and Lloyd published in Volume 85 of the Transactions of the Society of Naval Architects and Marine Engineers. FINCON predicts stabilized and unstabilized ship roll motion, bilge keel and antiroll fin sizing effects, and the influence of fin controller characteristics by use of a one degree-of-freedom roll-motion equation. Nonlinear roll damping characteristics, derived from model experiments or by other means, are incorporated by a combination of equivalent linearization and an iteration procedure. Results are predicted for short-crested seas (for stabilizer design purposes) and long-crested seas, which are described by two-parameter Bretschnieder wave spectra.

ADMINISTRATIVE INFORMATION

The development and documentation of the computer program reported herein is a part of the Conventional Ship Seakeeping Research and Development Program (Block SF 43 421 202) and the Ship Performance and Hydrodynamics Program (Block SF 43 421 001) both under Program Element 62543. At David W. Taylor Naval Ship Research and Development Center (DTNSRDC) it is identified by Work Units 1504-100, 1507-200, and 1500-104. Authors Susan L. Bales and Geoffrey G. Cox are DTNSRDC personnel. Author John R. Tucker is on the staff of Chi Associates, Inc.

INTRODUCTION

Devices such as bilge keels, anti-roll fins, and anti-roll tanks have been used over the years to reduce the roll motion of naval and commercial vessels. In recent years, the U.S. Navy has become increasingly involved in the design and development of suitable roll stabilization devices for Navy ships. This report provides a user's manual for a computer program which permits prediction of unstabilized and bilge keel/anti-roll, fin-stabilized, ship roll motions; bilge-keel and fin-sizing requirements; and the influence of fin controller characteristics. The program is known by the acronym FINCON.

The need for improved design and performance evaluation tools for bilge keels, antiroll fins, and their controllers has been recognized by Cox and Lloyd,[1*] who provide the hydrodynamic basis for such investigations. A comprehensive work, Reference 1 covers such topics as the current state-of-the-art for bilge keels, fins and tanks, the status of lateral motion predictions, measures of effectiveness, design practices, and sea state specifications for design. The computer program described in this report is based on the procedures detailed in Reference 1.

Reference 1 recognizes the potential need for roll and roll stabilization prediction tools throughout the so-called design spiral of U.S. Navy ships. Hence, the procedures outlined there and used here can be employed with a very simple descriptor of ship particulars and geometry. Specifically, modifications to the one-degree-of-freedom roll motion equation of Conolly[2] are used to predict ship roll motion, and the required program input is rather easy to obtain from the data available during early stages of ship design. For instance, in addition to specification of sea condition and ship speed, particulars such as ship length, beam displacement, transverse metacentric height and radius, natural roll period, and roll decay coefficients are required. The estimates of these required input variables can be refined as the design process continues and more accurate data becomes available through model experiments, etc. The manpower and computer time costs involved in such predictions are relatively low, and these predictions can be completed quickly in comparison to other seakeeping design evaluation procedures.

An added feature of the FINCON program is the capability to recognize the effect of fin saturation, which occurs in heavy seas, on RMS (root mean square) roll angle. The approach is based on a refinement of the method given in Appendix 3 of Reference 1, and specific details of this improvement will be published in a future report currently under preparation by Cox.

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*A complete listing of references is given on page 59.

PROGRAM ORGANIZATION

FINCON, written in extended FORTRAN, is operable on DTNSRDC's CDC 6000 computers.

Figure 1 is an overview of the organization of FINCON. The overall program consists of two major parts, FINCON and FINSTAB with FINCON acting as the driver or so-called main program.

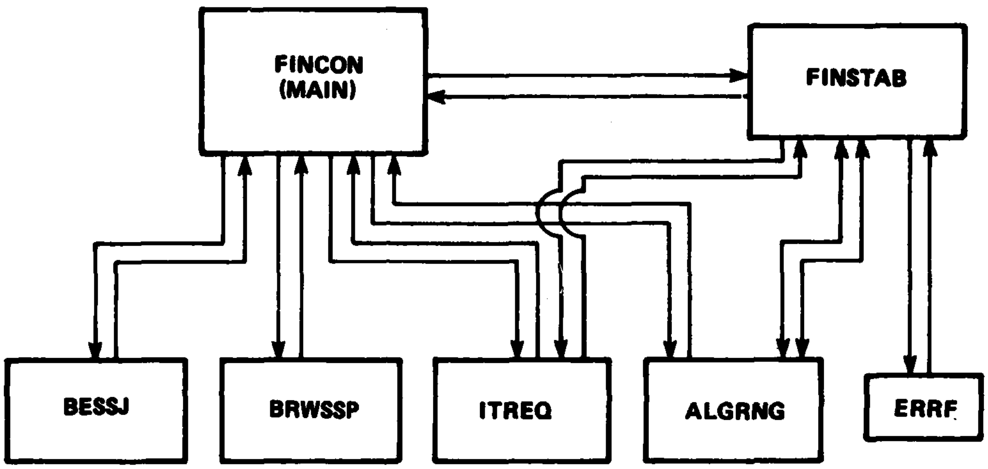

Figure 1 - Program Organization

As the driver of the rest of the program, FINCON calls all other routines for execution. In addition, FINCON provides the unstabilized roll calculations (including the effect of bilge keels) and is responsible for all program input and output.

FINSTAB is the second major part of the program. It predicts fin-stabilized roll angles, fin angles, fin angular velocities, and fin angular accelerations for the input fin and fin controller characteristics. FINSTAB also includes the fin saturation calculations. Although it is called into execution by FINCON, given the proper input and output specifications, FINSTAB in reality can be executed as an independent program.

BESSJ is a CDC system subroutine which is called up at the time of execution for calculation of Bessel functions of the first kind. BESSJ is only used when the ship's waterplane is declared elliptical.

BRWSSP is a subroutine to predict the Bretschnieder wave-slope spectrum for a specified significant wave height and modal wave period. Initially, the wave-height spectrum is computed; and then it is converted to a wave-slope spectrum by multiplying by the product of a constant and the square of the wave number k,

$$k = \omega^2/g \tag{1}$$

where ω is the wave frequency in radians per second and g is the acceleration due to gravity. The constant $(180/\pi)^2$ enters in to permit conversion into degrees to yield values of the roll-response amplitude operator, which is computed by FINCON in units of $(\text{degree/degree})^2$.

ITREQ is a subroutine which iterates between an equivalently linearized roll damping curve, which is a function of RMS roll rate, and the predicted RMS roll rate. In brief, the iteration continues until the computed short- or long-crested RMS roll rate, either unstabilized or stabilized, is within a small value, epsilon, of the previously computed value. The appropriate RMS roll angle can then be found. Additional details of the exact procedure are provided in the Appendixes A, B, and C. ITREQ is called by both FINCON and FINSTAB.

ERRF is a function subprogram which gives a rational approximation to the error integral

$$\text{erf}(\chi) = \frac{2}{\sqrt{\pi}} \int_0^{\chi} e^{-t^2}\, dt \tag{2}$$

and is used in the calculation of fin saturation effects.

ALGRNG is an integration subroutine which performs a so-called Lagrangian or quadratic integration over three points at a time. The subroutine is called by both FINCON and FINSTAB, and spectral closure is ensured by the techniques outlined in Figure 2, adopted from Reference 3.

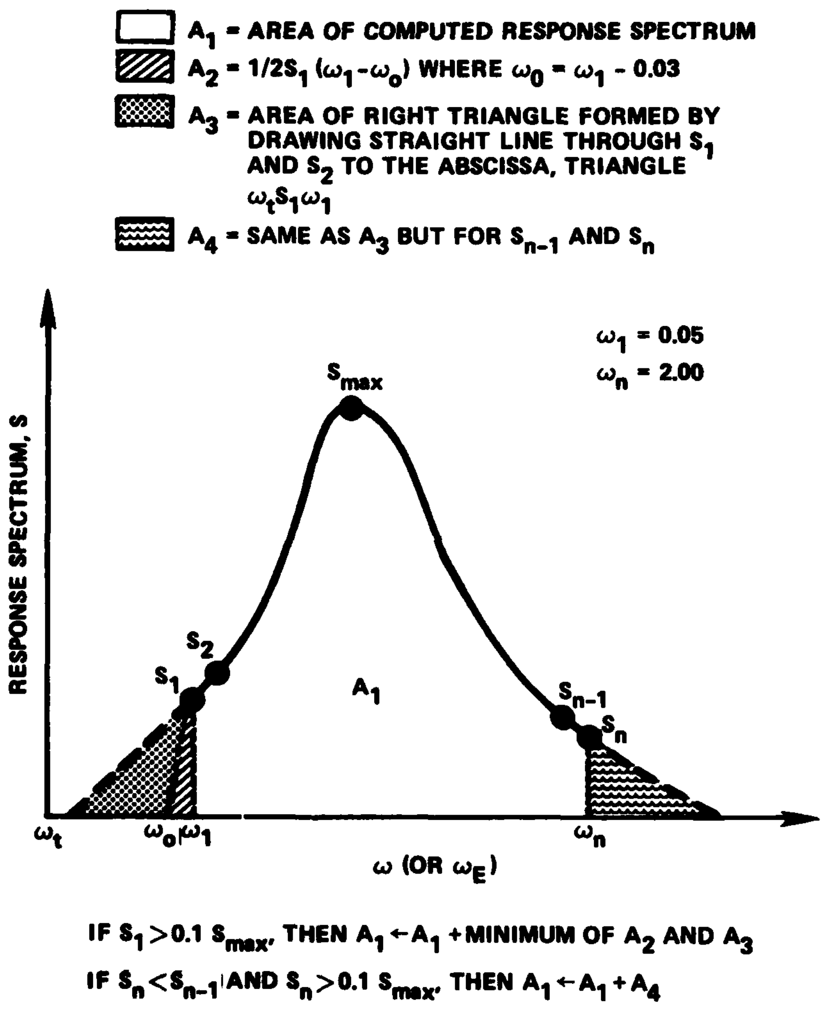

Figure 2 - Spectral Closure Procedure
(From Reference 3)

The procedure for predicting the unstabilized and stabilized roll angles, as well as fin angles, and velocities is outlined in Appendix A. Because the procedure is developed in detail in Reference 1, only a listing of the equations used is given in Appendix A. In general, the FORTRAN variables have been named as closely as possible to the variables of the equations of Appendix A, so the user should have relatively little difficulty in "reading" the program. A listing of the program is given in Appendix B. Appendix C describes two special algorithms used, namely the iteration algorithm and the cosine squared short-crested sea algorithm for arbitrary spreading angles.

PROGRAM INPUT

As described in the Introduction, the input requirements of FINCON are relatively simple. The input variables consist of sea conditions, ship speed, and very simple descriptions of the ship particulars and geometry. Unlike many multi-degree-of-freedom ship-motion prediction programs in use today, neither offsets of the ship sections nor Lewis forms are required. This makes implementation of FINCON possible at an early design stage (e.g., before the ship lines are "firmed up").

Table 1 describes the required input to the program and Table 2 explains the notation and variable names. Up to eight sea conditions and five ship speeds may be executed within a single run, using either metric or English units for input/output. If ITERATE on card 10 is greater than zero, then roll damping is treated as nonlinear, and coefficients, DUC, should be input. For example, letting d = DUC for a simpler notation, then

$$n = d_o + 1.61 d_p y^p + 1.88 d_1 y + 4 d_2 y^2 + 9.4 d_3 y^3 + 24 d_4 y^4 \qquad (3)$$

where $y = \sigma_{\dot{\phi}}/\omega_{\phi}$ is the RMS roll rate divided by ship natural frequency, p is 0.772, and n is the roll damping coefficient as a function of y.

TABLE 1 - INPUT TO FINCON PROGRAM

Card	Contents	Format
1	NAME1, NAME2, NAME3	(3A10)
2	TITLE2	(8A10)
3	NWH, NV, IUNITS	(3I5)
4	(SWH(IWH), IWH=1, NWH) where $1 \leq NWH \leq 10$	(8F10.5)
5	(TO(IWH), IWH=1, NWH) where $1 \leq NWH \leq 10$	(8F10.5)
6	(VK(IV), IV=1, NV) where $1 \leq NV \leq 5$	(5F10.5)
7	DISPTON, L, T, GM, BM, TPHI, Q	(7F10.5)
8	SHAPE	(A10)
9	ISC, ANGLE	(I5,F10.5)
10	ITERATE	(I5)
11	IF ITERATE = 0 ((DUC(IV,1), IV=1, NV) where $1 \leq NV \leq 5$	(5F10.5)
or		
11	IF ITERATE ≠ 0 ((DUC(IV,1), I=1, 6), IV=1, NV) where $1 \leq NV \leq 5$	(6F10.5)
12	IPRINT(1), IPRINT(2)	(2A10)
13	NSTAB	(I5)
	Repeat cards 14 through 17 NSTAB times.	
14	M, AREA, R	(I5,2F10.5)
15	DCLDBFS, H0, H1, H2, H3, H4	(6F10.5)
16	GK, GV, K1, K2, K3	(5F10.5)
17	A1, A2, A3, B1, B2, B3	(6F10.5)
18	NSAT	(I5)
19	(BSTOP (I), BVELMAX (I),I=1, NV)	(8F10.5)

TABLE 2 - PROGRAM NOTATION (INPUT)

ANGLE	Increment of wave energy spreading for calculation of short-crested responses; e.g., 5, 10, or 15 degrees
AREA	Fin area, square feet or square meters
A1, A2, A3	Fin servo coefficients
BM	Transverse metacentric radius, (distance between center of buoyancy and metacenter), feet or meters.
B1, B2, B3	Fin controller compensation coefficients
BSTOP	Fin limit angle
BVELMAX	Fin limit angular velocity
DCLDBFS	Free stream lift coefficient curve slope, per degree
DISPTON	Ship displacement, long tons or metric tons
DUC	Roll damping or roll damping coefficients
GK	Overall fin control gain
GM	Transverse metacentric height, feet or meters
GV	Speed dependent fin control gain
H0, H1, H2, H3, H4	Fin lift curve correction coefficients
IPRINT	Array of print options; IPRINT(1) = SPECTRA, heading printing of long-crested response spectra and components. IPRINT(2) = ITERATN, step by step printing of iteration over roll damping of relevant variables.
ISC	Switch for short-crested responses. If ISC $\neq$ 0, provide ANGLE.
ITERATE	Equals 0 for roll damping value independent of roll angle. Equals 1 when iteration is required.
IUNITS	Switch indicating type of units for Input/Output: IUNITS = 0 for English, = 1 for metric.
K1, K2, K3	Roll angle, velocity, and acceleration characteristic gain factors. Sensitivities of demanded fin angle to roll angle, velocity, and acceleration.
L	Ship length between particulars, feet or meters

TABLE 2 (Continued)

M	Number of fin pairs
NAME1, NAME2, NAME3	Identification of run of program by person's name, code, and telephone extension
NSAT	Equals 1 for inclusion of significant saturation effects
NSTAB	Number of fin/controller/servo, etc., input sets; e.g., ≤ 10
NV	Number of ship speeds, e.g., ≤ 5
NWH	Number of sea conditions, e.g., ≤ 10
Q	$\delta I/(I+\delta I)$, see Equation (5) for definition of $\delta I/I$
R	Fin moment arm, feet or meters
SHAPE	Alphameric description of waterplane shape; e.g., PARAB, ELLIP, or RECTANG
SWH	Significant wave height, feet or meters
T	Draft, feet or meters
TITLE2	Alphameric identification of a run of the program; e.g., ship name
TPHI	Roll period, seconds
TO	Modal wave period, seconds
VK	Ship speed, knots

The d_j values are found by fitting a curve* to experimentally derived calm water roll decay data, or by use of analytically predicted values, prior to execution of FINCON. The iteration is performed until

$$\left|1-(\hat{\sigma}_{\dot{\phi}}/y)\right| \leq 0.01 \qquad (4)$$

where $\hat{\sigma}_{\dot{\phi}}$ is that RMS roll rate obtained from the prediction using the roll damping coefficient n associated with y by Equation (3).

*In practice, a straight line frequently provides an adequate representation of the experimentally derived roll data.

Card 12 defines two print options. If IPRINT(1) is SPECTRA, a heading-by-heading printing of long-crested roll spectra and their components (e.g., the wave frequencies ω, the response amplitude operators (RAO's), etc.) will be printed. If IPRINT(2) is ITERATN, step-by-step printing of the iteration over roll damping of the relevant variables will occur. This option is useful for debugging purposes.

If NSTAB is zero on card 13, only unstabilized roll predictions will be made and cards 14 to 17 can be eliminated. If NSTAB is greater than zero, cards 14 to 17 should be repeated NSTAB times.

Card 18 specifies whether or not saturation calculations will be done. If NSAT is zero (blank card) no other cards are needed. If NSAT is greater than zero, NSAT pairs of values for fin limit angle (BSTOP) and fin limit velocity (BVELMAX) are needed. If BVELMAX is not supplied (field left blank) a value will be generated by FINCON (e.g., BVELMAX=10•BSTOP/TPHI).

Table 3 gives a sample listing of input cards for an example ship, between the END OF RECORD and END OF FILE cards. It should be noted that the input values are given in units of feet and long tons. A metric conversion option may be invoked to allow the input of values in metric units. The method for activating this option is to place a "1" in Column 15 (IUNITS) of card 3.

The first two data cards shown in Table 3 contain only alphanumeric, or descriptive data. Card 3, indicates that two sea conditions and one speed are to be considered and that English units are assumed for Input/Output. Cards 4 and 5 define the sea conditions in terms of significant wave height and modal wave period. Card 6 specifies the ship speed at 25 knots. Card 7 gives the ship particulars of displacement, length, draft, transverse metacentric height, transverse metacentric radius, roll period, and Q. Q is the ratio of added mass to total mass moment of inertia, $\delta I/(I+\delta I)$, and as shown in Reference 1, can be estimated from

$$\frac{\delta I}{I} = -0.186 + 1.179\ C_B - 0.615\ C_B^2 \text{ (without bilge keels)}$$

and (5)

$$\frac{\delta I}{I} = -0.002 + 0.814\ C_B - 0.316\ C_B^2 \text{ (with bilge keels)}$$

TABLE 3 - TYPICAL CONTROL AND DATA CARD SET

```
           CHHJZXX,CM77000,T199,P4.
           CHARGE,CHHJ,HQHAA15023,RS.
           ATTACH,OLDPL,FINCONREVISION6,ID=PUAA.
           MAP(ON)
           SETCORE(INDEF,ADDR)
           ATTACH(NSRDC)
           LIBRARY(NSRDC)
           FTN,I=OLDPL.
           LGO.
           7/8/9  END OF RECORD
Card  1:   H.JONES     1568      71210
      2:   CGN-42  SELECTED FINS (TWO FIN PAIRS,  75 SQ.FT.) R. N. O.  (25 KTS)
      3:       2    1    0
      4:      24.61      18.04
      5:      12.9       12.3
      6:      25.0
      7:   12000.0   560.0     22.7      4.3       16.06     12.8      0.331
      8:   PARAB
      9:       1      15.0
     10:       1
     11:   0.1693              0.00570   -.0002
     12:
     13:       1
     14:       2     75.0      33.45
     15:   0.43      0.349       1.117      -0.519
     16:   1.0       1.650     1.0       2.5       1.0
     17:   1.0       0.160     0.025     1.0       0.630     0.092
     18:       1
     19:      10.2       7.98875
           6/7/8/9  END OF FILE
```

where C_B is the block coefficient and average bilge keels are assumed. Card 8 specifies waterplane shape as parabolic, which is usual for fine-form naval ships. Card 9 indicates that short-crested seas will be treated and specifies the spreading angle to be 15 degrees. If card 9 were blank, the program would assume that only long-crested calculations would be done. Card 10 indicates that iteration over the roll-roll damping curve is required to account for nonlinear roll damping. Card 11 gives the coefficients, DUC or d, of the roll-roll damping curve (e.g., see Equation (3)). Had roll damping been linear in this sample input case, card 10 would have

been blank and card 11 would have contained the single value for roll damping coefficient, n, for 25 knots. Card 12 is blank, so printing of any intermediate steps (e.g., the long-crested spectra and their RAO's, etc., or the iteration steps) is not done.

Cards 1 to 12 provide all the data necessary to complete a FINCON run to calculate unstabilized roll angles. If card 13 were blank, this is exactly the way the program would execute. However, card 13 indicates that one set of stabilizing conditions is to be considered. Cards 14 to 17 provide the fin and fin controller particulars. Two pairs of 75 square feet fins with a fin moment arm of 33.45 feet are indicated on card 14. The fin moment arm is taken about the longitudinal axis, through the center of gravity, and measured to the center of the fin for all fin pairs. Card 15 gives the free stream, lift coefficient curve slope and the lift correction coefficients which compensate for fin-induced sway and yaw motions. The values of card 15 are estimated by the procedures outlined in Reference 1. Card 16 specifies both the overall gain G_K and speed dependent fin control gain G_V, as well as the roll angle, roll rate, and roll acceleration characteristic gains k_1, k_2, and k_3, such that the fin controller equation is

$$\beta = G_K \cdot G_V(k_1\phi + k_2\dot{\phi} + k_3\ddot{\phi}) \tag{6}$$

where ϕ is the roll angle and β is fin angle. Card 17 specifies the fin servo coefficients and the fin-controller compensation coefficients. The values given in Table 3 for card 17 variables were selected from Reference 4 and are also given in Reference 1.

Card 18 is not blank, indicating that any significant saturation effects will be included in the calculations, and so an additional card is required to provide the limiting angle and limiting speed* of the fins. Insignificant saturation effects are automatically ignored by the program.

---

*If the angle is provided and the speed is left blank, the program will compute an appropriate value.

This is to avoid the additional cost which would otherwise be incurred while having no significant effect on the results. Had card 18 been blank, indicating that no saturation effects were to be considered, then no other data cards would have been needed.

PROGRAM OUTPUT

Table 4 presents the program output for the sample input given in Table 3. The first page outputs the input identifying titles; the second page outputs the operating conditions and ship/fin/fin controller particulars; and the third page provides the results. The first listings on the third page gives the resulting unstabilized RMS roll angles and corresponding damping coefficient values for ship headings from 0 to 180 degrees (following to head seas) in 15-degree increments for short-crested seas. The next row of tables contains the corresponding RMS stabilized roll angles and damping coefficients, as well as the resulting RMS fin angles and velocities. Those values of RMS roll for which saturation effects would produce less than a 2 percent change are indicated by an asterisk. For such headings, only the unsaturated values are calculated.

Had there been a second stabilized condition specified on input card 13, another row of tables would follow the one for case 1. Results for additional speeds and sea conditions would be printed in a similar fashion on subsequent pages. The fourth page indicates that the program completed execution satisfactorily; e.g., no system (loader, input/output, etc.) errors were encountered.

Table 5 presents a typical output when IPRINT(1) is SPECTRA on card 12. One such page would appear for each ship heading. The columns provide wave frequency W, wave-encounter frequency WE, wavelength LAM, wavelength-to-shiplength LAM/L, wave number K, nondimensional transfer function TR, nondimensional response amplitude operator, RAO, wave-slope spectrum W SL S, and roll (unstabilized) response spectrum SUR. Also given are the dimensional response amplitude operator RAO DIM, the wave-height spectrum W HT S, and the resulting roll response spectrum SUR DIM, which should be equivalent to SUR. Due to the fact that this sample is for the case of nonlinear

TABLE 4 - TYPICAL PROGRAM OUTPUT, ITERATION OVER ROLL DAMPING

* * * ROLL MOTION PREDICTION PROGRAM * * *

H.JONES 1568 71210

TABLE 4 (Continued)

CGN-42

SIGNIFICANT WAVE HEIGHT(S) (FEET) =	24.01	18.04
MODAL WAVE PERIOD(S) (SECONDS) =	12.90	12.30
SHIP SPEED(S) (KNOTS) =	25.0	

DISPLACEMENT (L. TONS) =	12000.
LENGTH BETWEEN PP (FEET) =	500.0
DRAFT (FEET) =	22.70
TRANSVERSE METACENTRIC HEIGHT (FEET) =	4.3
METACENTER ABOVE BUOYANCY CENTER (FT) =	16.06
ROLL PERIOD (SECONDS) =	12.80
Q =	.331
WATERPLANE SHAPE =	PARAB
SPREADING ANGLE =	15.

ITERATION OVER ROLL DAMPING WILL BE DONE.

DAMPING INPUT IN THE FORM R = C1 + 1.01*C2*Y**0.772 + 1.88*C3*Y + 4.00*C4*Y**2 + 9.40*C5*Y**3 + 24.00*C6*Y**4

SPEED (KNOTS)	C1	C2	C3	C4	C5	C6
25.0	.1693	0.0000	.0057	-.0002	.0000	0.0000

ROLL STABILIZATION WILL BE CALCULATED FOR 1 CASES

FIN AND CONTROL SYSTEM PARAMETERS ARE AS FOLLOWS:

CASE	N	A FT SQ	R FT	(UCL/UB)FS PER DEG	H0	H1	H2	H3	H4	GK	GV	K1	K2	K3	A1	A2	A3	B1	B2	B3
1	2	75.00	33.45	.043	.349	1.117	-.519	0.000	0.000	1.000	1.650	1.000	2.500	1.000	1.000	.160	.025	1.000	.630	.092

IV	RSTOP	OVELMAX
1	18.20000	7.90875

TABLE 4 (Continued)

CGN-42

SIGNIFICANT WAVE HEIGHT = 24.61 FEET
MODAL WAVE PERIOD = 12.90 SECONDS
SHIP SPEED = 25.0 KNOTS

UNSTABILIZED RMS ROLL (DEGREES)

HEADING	N	SC
0	.1836	2.30
15	.1856	2.48
30	.1892	2.87
45	.1923	3.23
60	.1943	3.44
75	.1952	3.46
90	.1949	3.28
105	.1935	2.92
120	.1910	2.41
135	.1874	1.82
150	.1832	1.26
165	.1797	.85
180	.1783	.70

CASE 1: STABILIZED RMS ROLL (DEGREES) / FIN MOTION (DEGREES) / FIN VELOCITY (DEGREES/SECOND)

HEADING	N	SC		FIN MOTION (DEGREES) SC	FIN VELOCITY (DEGREES/SECOND) SC
0	.1776	1.36	*	2.64	.88
15	.1789	1.44	*	2.88	1.11
30	.1815	1.62	*	3.40	1.57
45	.1840	1.79	*	3.94	2.05
60	.1858	1.90	*	4.32	2.45
75	.1868	1.91	*	4.49	2.74
90	.1870	1.81	*	4.42	2.88
105	.1863	1.62	*	4.10	2.84
120	.1848	1.36	*	3.58	2.65
135	.1826	1.06	*	2.92	2.32
150	.1800	.78	*	2.24	1.92
165	.1778	.57	*	1.71	1.57
180	.1769	.50	*	1.51	1.43

* SATURATION FACTOR IS INSIGNIFICANT

TABLE 4 (Continued)

* * * E N D * * *

TABLE 5 - TYPICAL PROGRAM OUTPUT FOR IPRINT(1) = SPECTRA OPTION

CGN-42 SELECTED FINS (TWO FIN PAIRS, 75 SQ.FT.) R. N. O. (25 KTS)

SIGNIFICANT WAVE HEIGHT = 24.61 FEET
MODAL WAVE PERIOD = 12.90 SECONDS
SHIP SPEED = 25.0 KNOTS

SHIP HEADING = 90 DEGREES

W RAD/SEC	WE RAD/SEC	LAM FT	LAM/L	K DEG	TR DEG/DEG	RAO DEG/DEG SQ	W SL S DEGSQ SEC	SUR DEGSQ SEC	RAO DIM DEG/FT SQ	W HT S FTSQ SEC	SUR DIM DEGSQ SEC
.050	.050	80850.310	144.390	.004	1.006	1.012	0.000	0.000	.000	0.000	0.000
.100	.100	20214.570	36.097	.016	1.025	1.051	0.000	0.000	.000	0.000	0.000
.150	.150	8984.257	16.043	.040	1.059	1.122	.000	.000	.002	.000	.000
.200	.200	5053.644	9.024	.071	1.114	1.240	.000	.000	.006	.000	.000
.250	.250	3234.332	5.776	.111	1.196	1.431	.000	.000	.016	.000	.000
.300	.300	2246.064	4.011	.160	1.321	1.746	.019	.033	.045	.741	.033
.350	.350	1650.170	2.947	.218	1.512	2.287	.000	2.032	.109	18.665	2.032
.400	.400	1263.411	2.256	.285	1.791	3.208	5.409	17.354	.260	66.624	17.354
.450	.450	998.251	1.783	.361	2.072	4.295	13.502	57.994	.559	103.026	57.994
.500	.500	808.583	1.444	.445	1.934	3.739	21.922	81.966	.741	110.595	81.966
.550	.550	668.250	1.193	.539	1.370	1.876	28.475	53.427	.545	98.115	53.427
.600	.600	561.516	1.003	.641	.902	.815	32.720	26.651	.335	79.604	26.651
.650	.650	478.452	.854	.752	.612	.374	35.047	13.112	.212	61.904	13.112
.700	.700	412.542	.737	.873	.432	.187	36.006	6.720	.142	47.203	6.720
.750	.750	359.370	.642	1.002	.317	.100	36.066	3.619	.101	35.940	3.619
.800	.800	315.853	.564	1.140	.240	.050	35.566	2.052	.075	27.378	2.052
.850	.850	279.787	.500	1.287	.188	.035	34.736	1.228	.059	20.981	1.228
.900	.900	249.563	.446	1.443	.152	.023	33.722	.779	.040	16.206	.779
.950	.950	223.984	.400	1.607	.127	.016	32.620	.523	.041	12.620	.523
1.000	1.000	202.146	.361	1.781	.109	.012	31.490	.371	.037	9.929	.371
1.050	1.050	183.352	.327	1.963	.095	.009	30.367	.275	.035	7.877	.275
1.100	1.100	167.063	.298	2.155	.085	.007	29.273	.212	.034	6.304	.212
1.150	1.150	152.851	.273	2.355	.077	.006	28.220	.168	.033	5.087	.168
1.200	1.200	140.379	.251	2.564	.070	.005	27.215	.135	.033	4.130	.135
1.250	1.250	129.373	.231	2.783	.064	.004	26.260	.109	.032	3.391	.109
1.300	1.300	119.613	.214	3.010	.059	.003	25.356	.089	.032	2.799	.089
1.350	1.350	110.917	.198	3.246	.054	.003	24.501	.072	.031	2.326	.072
1.400	1.400	103.136	.184	3.491	.050	.002	23.694	.059	.030	1.945	.059
1.450	1.450	96.145	.172	3.744	.045	.002	22.932	.047	.029	1.636	.047
1.500	1.500	89.843	.160	4.007	.041	.002	22.213	.038	.027	1.383	.038
1.550	1.550	84.140	.150	4.279	.037	.001	21.533	.030	.026	1.176	.030
1.600	1.600	78.963	.141	4.559	.034	.001	20.890	.024	.024	1.005	.024
1.650	1.650	74.250	.133	4.848	.030	.001	20.282	.019	.022	.863	.019
1.700	1.700	69.947	.125	5.147	.027	.001	19.707	.015	.020	.744	.015
1.750	1.750	66.007	.118	5.454	.024	.001	19.161	.011	.018	.644	.011
1.800	1.800	62.391	.111	5.770	.022	.000	18.644	.009	.016	.560	.009
1.850	1.850	59.064	.105	6.095	.019	.000	18.153	.007	.014	.489	.007
1.900	1.900	55.996	.100	6.429	.017	.000	17.686	.005	.012	.428	.005
1.950	1.950	53.161	.095	6.772	.015	.000	17.242	.004	.010	.376	.004
2.000	2.000	50.536	.090	7.124	.013	.000	16.810	.003	.009	.331	.003

RMS ROLL = 3.60 DEGREES

roll damping, the spectral data and the RMS roll of Table 5 are not, in general, considered especially meaningful. Had the damping been linear, as is usually the case for the ship without bilge keels, the spectra would be representative of the long-crested seas case and the RMS roll could correspond to a value given on the "page-three-type-output" of Table 4.

Table 6 presents a typical output when IPRINT(2) is ITERATN on card 12. In brief, the intermediate roll rate and damping coefficient values are printed for each heading, speed, and sea condition. Appendix C further describes this output example.

TABLE 6 - TYPICAL PROGRAM OUTPUT FOR IPRINT(2) = ITERATN OPTION

IV	IMU	NTRY	PHIN	YP+1	YP	YP-1	GP	GP-1
1	7	1	.094	.475	0.000	.239	4.628	.476
1	7	1	.094	.475	2.314	0.000	4.628	4.628
1	7	2	.140	.475	2.314	0.000	3.847	4.628
1	7	2	.140	3.461	3.461	2.314	3.847	3.847
1	7	3	.156	3.461	3.461	2.314	3.674	3.847
1	7	3	.156	3.645	3.645	3.461	3.674	3.674
1	7	4	.159	3.645	3.645	3.461	3.652	3.674
1	7	1	.094	3.645	0.000	3.461	.507	3.674
1	7	1	.094	3.645	.254	0.000	.507	.507
1	7	2	.100	3.645	.254	0.000	.506	.507
1	7	2	.100	.504	.504	.254	.506	.506
1	7	3	.105	.504	.504	.254	.504	.506

PROGRAM EXECUTION

A typical deck control card set up is given in Table 3. Simply speaking, the object program is attached and executed. The object program is stored permanently on a private disk pack and can be recovered for storage on the main (public) disk and for user execution by running the control card deck of Table 7. The source deck is also stored on the private disk pack in an UPDATE file such that program modifications can be easily made, if necessary. The program listing of Appendix B was printed from this UPDATE file.

TABLE 7 - CONTROL CARD SET TO RETRIEVE OBJECT PROGRAM

```
COLS.  123456789112345678921234567893123456789412345678951234567896123456789

       CHHJPAK,CM77777,T100,RP1,P3.
       CHARGE,CHHJ,XXXXXXXXXX,CC,R.
       PAUSE.   JOB REQUIRES DISK PACK DV4850.
       MOUNT,VSN=DV4850,SN=HJPKL4.
       REQUEST,TWO,*PF.
       ATTACH,ONE,FINCONOBJECTNOV,ID=CHHJ,CY=1,MR=1,SN=HJPKL4.
       COPYBF,ONE,TWO,1.
       CATALOG,TWO,FINCONOBJECTNOV,ID=PUAA,AC=XXXXXXXXXX,CY=1,MR=1.
       6/7/8/9  END OF FILE
```

The run time of the program, indicated by TXXX on the job card of Table 3, varies, of course, with the amount of calculation required. Roughly, for nonlinear roll damping and 15-degree short-crested spreading, a stabilized roll calculation (without saturation effects, and for a single sea condition and speed) takes about 50 seconds of execution time and 15 seconds compilation time. For unstabilized calculations, the execution time is somewhat less than half of the time for the stabilized case. The time increases proportionately as the spreading angle of the short-crested seas is decreased. For a 5-degree spreading angle, the time is almost three times ($\sim$ 145 seconds) that of the 15-degree case (reflecting the fact that there are about three times as many calculations that need to be performed). From the runs made to date, it is not evident that decreasing the spreading angle from 15 degrees increases the accuracy of predicted roll at a given ship heading by a noticeable amount. However, a finer mesh of spreading angles does, in some cases, permit a more refined localization of the worst heading angle. Thus, the required execution time is a multiple of 50 seconds depending on the number of speeds, sea conditions, and the value of the spreading angle (in proportion to 15 degrees).

The required memory, as indicated by CMXXXXXX on the job is 77777 octal words (see Table 3). The job priority, indicated by PX on the job card, is then determined by the amount of system time required. Based on current computer center figures for the CDC 6700 and average costs over several program runs, the guidelines in Table 8 are offered.

TABLE 8 - RUN TIME AND COST GUIDELINES

T	Highest Priority (Turnaround)	∿ $/System Seconds
< 200	4 (prime shift, 1 hour max after completion)	0.090
<3600	3 (prime shift, as soon as possible)	0.074
Unlimited	2 (nonprime shift, when possible, overnight)	0.060

PROGRAM VERIFICATION

Predicted values of unstabilized ship roll motion using the one-degree-of-freedom roll motion procedure, have been compared to model and full-scale experiment results in both References 1 and 2. Ongoing work at DTNSRDC by Meyers has found the results of the single-degree equation very similar to those of the coupled, three-degree equations for roll-sway-yaw for the worst heading roll motion, although some underprediction in bow seas and some overprediction in following to quartering seas have been noted. Additionally, Reference 2, as well as work by Lloyd and other Admiralty Marine Technology Establishment (AMTE) personnel, has substantiated, at least in part, the stabilized roll and fin predictions. It is generally recognized that the predictions of FINCON (e.g., for the worst heading) are appropriate for use in design problems.

The coding of FINCON has been verified by making comparisons with results of the older unpublished FINS program, as well as with published results of programs currently used by Lloyd and others at AMTE. The comparisons substantiate the correctness of the coding of FINCON in general, though some differences do occur between the results of FINCON and the

AMTE program. For example, at some speeds, the FINCON unstabilized roll angles were higher than the corresponding AMTE values for the same narrow-beam LEANDER-class frigate evaluated for the case when roll damping is independent of roll angle. The differences may be due to differences in the input, slight differences in the motion equations and algorithms programmed, or differences in the short-crested seas algorithm. One known difference is that FINCON accepts as input the true value for BM, the center of buoyancy; whereas the AMTE program computes a value based on the shape of the waterplane. Another difference, though not relevant to the comparisons made for the LEANDER, is that the AMTE program has no provision to handle the case when roll damping is dependent on roll angle.

FUTURE WORK

FINCON is the first of a series of new tools being developed to enhance the U.S. Navy's roll/fin design capability. As such, FINCON is the basis for all such current and near-future investigations. Specific guidelines for optimum use of the program in the form of a rather complete design exercise can be found in Reference 1. Procedures for evaluating bilge-keel and fin sizing and stabilizer control optimization are detailed there. These procedures indicate how the use of the FINCON program in roll/fin/controller design practice can be extremely instructive.

Another very important area currently being investigated by Cox is the use of a coupled, three-degree system of equations for roll, sway, and yaw motion prediction. A more general and refined program is being developed in conjunction with that work. The program under development will also be of practical use at an early stage of ship design, requiring only very simple input requirements. A complete report and user's manual for the improved three-degree-of-freedom simulation system will soon be published. It will include details of the approach which is used in the current one-degree-of-freedom program to recognize fin-saturation effects.

CONCLUDING REMARKS

This report provides a user's guide to FINCON, a roll, fin, fin controller prediction computer program. No attempt to describe design

practices or the required engineering decisions necessary to using this tool has been made; Reference 1 provides a comprehensive discussion of such materials. Sample inputs and outputs, as well as a description of the program organization and procedures have been given. It is envisioned that the engineer, with a working knowledge of Reference 1, will run the program essentially as a "black box"--he/she is not expected to need to contend with the actual FORTRAN or source deck; and, thus, only a very rudimentary knowledge of programming or computers is required. Instead, he/she will be required to actively participate in the engineering tradeoff decisions necessary in design work, and, as such will probably run FINCON several times in any given investigation.

APPENDIX A

PROGRAM PROCEDURE AND FLOW

The equations solved in FINCON are listed in Table 9 and are taken almost exclusively from Reference 1. For purposes of illustration, a short-crested spreading angle of 10 degrees is assumed. Table 10 provides a description of the nomenclature used in Table 9. The corresponding FORTRAN notation (e.g., see the listing of Appendix B) follows as closely as possible that of Table 10.*

Table 9 is, in a sense, broken into three algorithmic steps. Four basic predictions are identified: stabilized roll, roll rate, fin angle, and fin velocity. Each of the four is identified by a more or less reverse building-block procedure. For example, the final step of the first algorithm is labeled 1-1, the step preceding 1-1 is 1-2, the step preceding 1-2 is 1-3, etc. Similarly, steps 2-1, 2-2, etc., and 3-1, 3-2, etc., are developed. It is felt that this reverse building-block approach to listing the steps makes it easier to see the final results and is also representative of the procedure followed in organizing the equations of Reference 1 for programming purposes. Obviously some of the steps developed for the first algorithm are needed by the other two algorithms (e.g., step 1-4-1); however, it was not considered necessary to repeat these for each of the other two. Instead, for clarity, one can assume that the results of each step of the first algorithm are available to the remaining algorithms.

Figure 3 presents a diagram of the flow sequence of FINCON. The figure identifies the important loops over sea conditions and ship speed for both unstabilized and stabilized predictions. The diagram was constructed with the intent of providing a quick overview of the entire program flow so that major computational segments are easily identified.

---

*One exception to this is that c_u in Table 9 becomes CA in the FORTRAN.

TABLE 9 - EQUATIONS FOR ROLL, FIN ANGLE, AND FIN VELOCITY CALCULATION

1-1 $$\left[\sigma_{\phi_s}(\mu)\right]^2_{sc} = \frac{1}{9} \sum_{p=-8}^{8} \cos^2\left(\frac{p\pi}{18}\right)\left[\sigma_s\left(\mu + \frac{p\pi}{18}\right)\right]^2_{\ell cn}$$

2-1 $$[\sigma_{\dot{\phi}}(\mu)]^2_{sc} = \frac{1}{9} \sum_{p=-8}^{8} \cos^2\left(\frac{p\pi}{18}\right)\left[\sigma_{\dot{\phi}}\left(\mu + \frac{p\pi}{18}\right)\right]^2_{\ell cn}$$

3-1 $$[\sigma_{\beta}(\mu)]^2_{sc} = \frac{1}{9} \sum_{p=-8}^{8} \cos^2\left(\frac{p\pi}{18}\right)\left[\sigma_{\beta}\left(\mu + \frac{p\pi}{18}\right)\right]^2_{\ell cn}$$

4-1 $$[\sigma_{\dot{\beta}}(\mu)]^2_{sc} = \frac{1}{9} \sum_{p=-8}^{8} \cos^2\left(\frac{p\pi}{18}\right)\left[\sigma_{\dot{\beta}}\left(\mu + \frac{p\pi}{18}\right)\right]^2_{\ell cn}$$

1-2 $$[\sigma_s(\nu)]^2_{\ell cn} = \int_0^{\omega^*} S_{\phi_u}\,[\omega,\omega_E(\omega),\nu,n_u]\left(\frac{\phi_s}{\phi_u}\right)^2 d\omega$$

2-2 $$[\sigma_{\dot{\phi}}(\nu)]^2_{\ell cn} = \int_0^{\omega^*} S_{\dot{\phi}_u}\,[\omega,\omega_E(\omega),\nu,n_u]\left(\frac{\phi_s}{\phi_u}\right)^2 d\omega$$

3-2 $$[\sigma_{\beta}(\nu)]^2_{\ell cn} = \int_0^{\omega^*} S_{\phi_u}\,[\omega,\omega_E(\omega),\nu,n_u]\left(\frac{\phi_s}{\phi_u}\right)^2 \frac{[(\beta_a)_o/\phi_s]^2}{a_R^2+a_I^2}\, d\omega$$

4-2 $$[\sigma_{\beta}(\nu)]^2_{\ell cn} = \int_0^{\omega^*} S_{\phi_u}\,[\omega,\omega_E(\omega),\nu,n_u]\left(\frac{\phi_s}{\phi_u}\right)^2 \frac{[(\beta_a)_o/\phi_s]^2}{a_R^2+a_I^2}\, \omega_E^2 d\omega$$

TABLE 9 (Continued)

1-3-1 $S_{\dot{\phi}_u}[\omega,\omega_E(\omega),\nu,n_u] = S_{\phi_u}[\omega,\omega_E(\omega),\nu,n_u](\omega_E(\omega))^2$

1-3-2 $S_{\phi_u}[\omega,\omega_E(\omega),\nu,n_u] = S_\alpha(\omega)\left[T_{\phi_u}(\omega_E,\nu,n_u)\right]^2$

1-3-3 $S_\alpha(\omega) = \left\{\frac{487.0626}{T_o^4\omega^5}(\tilde{\zeta}_w)^2_{1/3}\exp\left[\frac{-1948.2444}{T_o^4\omega^4}\right]\right\}\left(\frac{360\ \omega^2}{2\pi\ g}\right)$

1-3-4 $T_{\phi_u}(\omega_E,\nu,n_u) = \frac{\phi_u}{k_{\zeta_a}} = \frac{e^{-kT}}{c_u}\sin\nu(h^2+C^2b_u^2)^{1/2}$

1-3-5 $k = 2\pi/\lambda = \omega^2/g;\ c_u = (a^2+b_u^2)^{1/2};\ a = 1-\Lambda^2;$

$\Lambda = \omega_E/\omega_\phi;\ b_u = 2n_u\Lambda;\ h = D - qC\Lambda^2;$

$D = \frac{\sin k_L}{k_L}$ or $F_p + \frac{BM}{GM}G_p$ or $F_e + \frac{BM}{GM}G_e$ for

rectangular, parabolic, or elliptical waterplanes, respectively;

$k_L = \frac{1}{2}kL\cos\nu = \frac{1}{2g}\omega^2L\cos\nu;$

$F_p = \frac{3}{k_L^3}[\sin k_L - k_L\cos k_L];$

$G_p = \frac{1575}{k_L^7}\left[\left(1-\frac{2k_L^2}{5}\right)\sin k_L - \left(k_L-\frac{k_L^3}{15}\right)\cos k_L\right] - F_p;$

TABLE 9 (Continued)

$$F_e = \frac{2}{k_L} J_1(k_L);$$

$$G_e = \frac{8}{k_L^2} [F_e - J_o(k_L)] - F_e;$$

$$C = \frac{\sin k_L^*}{k_L^*}; \; k_L^* = \frac{1}{2} kL^* \cos \nu;$$

L^* = L, 1/2 L, or $\sqrt{7}/4$ L for rectangular, parabolic, or elliptical waterplane, respectively;

1-4-1 $$\left(\frac{\phi_s}{\phi_u}\right)^2 = \left(\frac{c_u}{c_s}\right)^2 \left[1+2\left(\frac{s_a}{c_s\phi_s}\right)\left(\frac{a}{c_s}\cos\xi + \frac{b_s}{c_s}\sin\xi\right) + \left(\frac{s_a}{c_s\phi_s}\right)^2\right]^{-1}$$

1-4-2 $$c_s = (a^2+b_s^2)^{1/2}; \; b_s = 2n_s\Lambda$$

1-4-3 $$\frac{s_a}{c_s\phi_s} = S_{sm} \left(\frac{\rho V^2}{\Delta GM}\right) MAR \left(\frac{dC_L}{d\beta}\right) E \frac{1}{c_s(a_R^2+a_I^2)^{1/2}} \frac{(\beta_a)_o}{\phi_s}$$

1-4-4 $$\sin\xi = \frac{k_I(a_Rb_R-a_Ib_I)-k_R(a_Rb_I+a_Ib_R)}{[(k_R^2+k_I^2)(a_R^2+a_I^2)(b_R^2+b_I^2)]^{1/2}};$$

$$\cos\xi = \frac{k_R(a_Rb_R-a_Ib_I)+k_I(a_Rb_I+a_Ib_R)}{[(k_R^2+k_I^2)(a_R^2+a_I^2)(b_R^2+b_I^2)]^{1/2}}$$

TABLE 9 (Continued)

1-4-5 $$\frac{(\beta_a)_o}{\phi_s} = G_k \cdot G_V \left[\frac{k_R^2+k_I^2}{b_R^2+b_I^2}\right]^{1/2};$$

$$k_R = k_1 - \omega_E^2 k_3;\ k_I = \omega_E k_2;\ b_R = b_1 - \omega_E^2 b_3;$$

$$b_I = \omega_E b_2;\ a_R = a_1 - \omega_E^2 a_3;\ a_I = \omega_E a_2;$$

$$\left(\frac{dC_L}{d\beta}\right)_E = h_F(\omega_E)\left(\frac{dC_L}{d\beta}\right)_{FS};\ h_F(\omega_E) = h_o + h_1\omega_E + h_2\omega_E^2$$

$$+ h_3\omega_E^3 + h_4\omega_E^4;$$

$$\omega_E = \omega - \frac{\omega^2}{g} V \cos \nu$$

1-5-1 $$S_{sm} = \frac{1}{(1-x_2)}\left[(1-Fx_2)\ \mathrm{erf}\left(\frac{\beta_{stp}}{\sigma_\beta\sqrt{2}}\right) + (F-1)x_2\ \mathrm{erf}\left(\frac{\beta_{stp}}{x_2\sigma_\beta\sqrt{2}}\right)\right]$$

1-5-2 $$F = \left(\frac{4}{\pi}\right)\left(\frac{x_2}{x_1}\right)$$

1-5-3 $$x_1 = \left(\frac{\beta_{stp}}{\dot{\beta}_{max}}\right)\left(\frac{\sigma_{\dot{\beta}}}{\sigma_\beta}\right)$$

TABLE 10 - NOTATION USED IN EQUATIONS OF TABLE 9

A	Fin area
a	$1 - \Lambda^2$
a_I	$\omega_E a_2$
a_R	$a_I - \omega_E^2 a_3$
a_1, a_2, a_3	Fin servo coefficients
BM	Distance between center of buoyancy and metacenter
b_I	$\omega_E b_2$
b_R	$b_1 - \omega_E^2 b_3$
b_1, b_2, b_3	Fin controller compensation coefficients
$c_{u,s}$	$(a^2 + b_{u,s}^2)^{1/2}$
$(dC_L/d\beta)_E$	Effective lift curve slope
$(dC_L/d\beta)_{FS}$	Free stream lift coefficient curve slope
GM	Transverse metacentric height
G_k	Fin controller overall gain control
G_V	Fin controller velocity dependent gain control
g	Acceleration due to gravity
$h_F(\omega_E)$	Ratio of effective to free stream fin lift curve slopes
h_o, h_1, h_2, h_3, h_4	$h_F(\omega_E) = h_o + h_1\omega_E + h_2\omega_E^2 + h_3\omega_E^3 + h_4\omega_E^4$
J_o, J_1	Bessel functions of the first kind
k	Wave number, ω^2/g
k_I	$\omega_E k_2$
k_R	$k_1 - \omega_E^2 k_3$

TABLE 10 (Continued)

k_1, k_2, k_3	Roll angle, velocity, and acceleration characteristic gain values
L	Ship length between perpendiculars
M	Number of fin pairs
n_u	Roll decay coefficient (ship without fins)
q	$\delta I/(I+\delta I)$, see Equation (5) for definition of $\delta I/I$
R	Fin moment arm (about a longitudinal line through the ship center of gravity)
S_{sm}	Saturation multiplier
S_α	Wave-slope spectral coordinate
S_{ϕ_u}	Unstabilized roll response
T	Mean ship draft
T_o	Modal (peak) period of wave-height spectrum
T_{ϕ_u}	Unstabilized roll transfer function
V	Ship speed
$\beta(\beta_a)$	Fin angle (amplitude)
β_{stp}	Fin limit angle
$\dot{\beta}_{max}$	Fin limit velocity
Δ	Ship displacement weight
ζ_a	Wave amplitude
$(\tilde{\zeta}_w)_{1/3}$	Significant wave height
Λ	Tuning factor, ω_E/ω_ϕ
λ	Wavelength
μ	Ship heading, with respect to the ship, of predominant wave direction

TABLE 10 (Continued)

ν	Wave direction, with respect to the ship, apart from the predominant direction
ρ	Density of seawater
σ_s	Stabilized root mean square roll angle
σ_β	Root mean square fin angle
$\sigma_{\dot{\beta}}$	Root mean square fin velocity
ϕ_s	Stabilized roll angle amplitude
ϕ_u	Unstabilized roll angle amplitude
ϕ_s/ϕ_u	Roll reduction factor
ω	Wave frequency
ω_E	Frequency of wave encounter
ω_ϕ	Ship natural roll frequency
ω^*	Frequency above which roll response is negligible, 2 radians/second

Subscripts

ℓcn	Long-crested
sc	Short-crested
s	Stabilized
u	Unstabilized

FINCON PROGRAM FLOW

```
I/O
Initialize
Calculate cos^2 values
DO 700 (Sea Conditions)
     Calculate 2-Param. Wave Slope Spectrum
     DO 600 (Ship Speed)
          DO 500 (Predominant Wave Direction)
               Initialize
               80 Next unstabilized roll damping value
               DO 400 (Spreading Angle)                                  (Unstabilized Roll)
                    Initialize
                    DO 200 (Wave Frequency)
                         Initialize
                         Calculate values dependent on wave frequency
                         Calculate unstabilized roll transfer function
                         Calculate unstabilized roll spectrum (long crested only)
                    200 End-of-Loop
                    Calculate unstabilized RMS  roll
                    If no iteration, store long crested roll values
               400 End-of-Loop
               Sum short crested components
               Iteration over roll damping required?
                  No - go to step 250
                  Yes - if number of attempts > 10, write message and go to step 900
                      - if closed go to step 250
                      - otherwise perform iteration procedure
                        and go to step 80
                    If requested, output long crested spectrum and its components
               250 If stabilized roll calculations not required go to step 500
               DO 280 (Stabilizing Cases)                (Stabilized Roll, Fin, Fin Velocity)
                    80* Next stabilized roll damping value
                    DO 400* (spreading Angle)
                         DO 200* (Wave Frequency)
                              Initialize
                              Calculate effective lift curve slope
                              Calculate fin to roll angle amplitude
                              Calculate roll reduction factor
                              Calculate stabilized roll, fin motion, and fin
                              velocity spectra
                         200* End-of-Loop
                         Calculate stabilized roll, roll rate, fin angle, and fin
                         velocity
                         If no iteration, store long crested roll values
                         Sum Short crested components, if requested
                    400* End-of-Loop
                    Iteration over roll damping required?
                       No - go to 250*
                       Yes - If number of attempts > 10, write message and go to
                       step 900
                           - If closed go to step 250*
                           - Otherwise perform iteration procedure and
                             go to step 80*
               250* No (further) damping iteration required
               280 End-of-Loop
          500 End-of-Loop
          Output results
     600 End-of-Loop
700 End-of-Loop
900 End of run message
```

Note: RMS = root mean square.

Figure 3 - Diagram of Program Flow Sequence

APPENDIX B
PROGRAM LISTING

A complete listing of FINCON is given on the subsequent pages. The routines are listed in the order FINCON, ITREQ, BRWSSP, ALGRNG, FINSTAB, and ERRF. BESSJ is a system routine and hence not given here. The listing, made from an UPDATE file stored on a private disk pack, contains a unique identification of each line of coding on the far right-hand side of the pages. This identification first identifies the routine by a name (e.g., ROLL, TREQ, BWSS, ALGR, and FST) and then by a line number.

The FORTRAN is embedded with comment cards for identification of the steps of the prediction procedure. Modifications can easily be made to this source coding by inserting or deleting statements anywhere in the routines via an "UPDATE" run of the program.

```
      PROGRAM FINCON (INPUT=512,OUTPUT=512,TAPE5=INPUT,TAPE6=OUTPUT,
     2               TAPE1)
*
*CDC 6700 - - - MARCH, 1976 - - - DTNSRDC - - - CODE 1568, SUSAN BALES
* J. R. TUCKER, - - AUGUST, 1979 - - CHI ASSOCIATES, INC., ROSLYN, VA.
*FORTRAN PROGRAM TO PREDICT ROLL MOTION ....UNSTABILIZED MOTION PREDICTE
*USING THE THEORY OF J. E. CONOLLY MODIFIED TO ALLOW FOR NONLINEAR
*DAMPING.  STABILIZED MOTION PREDICTED USING COX AND LLOYD.
*
C THIS VERSION OF FINCON (TPSC78) WRITES TO PF THE SHORTCRESTED STAB.
C OR UNSTAB. ROLL RESPONSES (RMS).  THIS FILE IS DESIGNED TO BE POST
C PROCESSED FOR USE WITH THE POLAR PLOT PROGRAM.
C
      INTEGER SHAPE,PARAB,ELLIP,RECTANG,SPECTRA
      REAL KL,KLPRIME,L,NUR,MUR,MOUR,LPRIME,LAM,LAMCNL,K1,K2,K3,M
        COMMON/ITRTN/STAT,PRCN,NTRY,KMU,KNU,KV,GP,GPM1,YPM1,YP,YPP1,
     2 PHIN,IPRINT(8),ITERATE,WPHI
      COMMON /STAB/ NSTAB,M(10),AREA(10),R(10),DCLDBFS(10),H0(10),
     2 H1(10),H2(10),H3(10),H4(10),GK(10),GV(10),K1(10),K2(10),K3(10),
     2 A1(10),A2(10),A3(10),B1(10),B2(10),B3(10),DAMPU(13),DAMPS(10,13),
     2  DUC(5,6),SSIGLC(10,13),NNU,ILC,ISC,WE(40,35),
     2  SSIGVLC(10,13),SSIGVSC(10,13),
     2 SUR(40,35),W(40),NW,COS1(35),CON1,SSIGSC(10,13),
     2 VFS(5),DISPLB,GM , BMOTLC(10,13),
     2  BMOTSC(10,13),BVELSC(10,13),BVELLC(10,13),BSTOP(5),BVELMAX(5)
     2  ,NSAT,ITEST(10,13)
      DIMENSION TITLE2(8),EKT(40),P(35),S(40),SWH(10),TO(10),VK(5),
     2 MUR(13),MUD(13),NUR(35),SINNU(35),COSNU(35),SIGSQSC(13),SIGSC(13)
     2,SIGLC(13),TR(40),MOUR(35),BESSEL(100),SURV(40,35)
     2  ,SGVSQSC(13),SIGVSC(13),VMOUR(35),SIGVLC(13),SWMET(10)
      DATA SPECTRA,ITERATN/7HSPECTRA,7HITERATN/
      DATA MUD/0,15,30,45,60,75,90,105,120,135,150,165,180/
      DATA PI,RHO,GRAVITY/3.1415926,1.99,32.1725/
      DATA PARAB,ELLIP,RECTANG/10HPARAB     ,10HELLIP     ,
     210HRECTANG   /
      DATA NW/40/    , NMU/13/   ,EPS/.0001/,     WDEL/.05/
*
*INPUT AND OUTPUT THE SEA AND SHIP CONDITIONS FOR UNSTABILIZED ROLL
*CALCULATIONS.
*
      READ (5,1000) NAME1,NAME2,NAME3
      WRITE (6,2000)           NAME1,NAME2,NAME3
      READ  (5,1000) TITLE2
      WRITE (6,2001) TITLE2
      READ  (5,1001) NWH,NV,IUNITS
      WRITE (1) NWH,NV
      READ  (5,1002) (SWH(I),I=1,NWH)
*
     IF (IUNITS .EQ. 0) GO TO 5
      WRITE (6,3002) (SWH(I),I=1,NWH)
     GO TO 6
*
    5 WRITE (6,2002) (SWH(I),I=1,NWH)
    6 CONTINUE
      READ  (5,1002) (TO(I),I=1,NWH)
      WRITE (6,2003) (TO(I),I=1,NWH)
      READ  (5,1002) (VK(I),I=1,NV)
```

```
      WRITE (6,2008) (VK(I),I=1,NV)
      READ  (5,1002) DISPTON,L,T,GM,BM,TPHI,Q
*
     IF (IUNITS .EQ. 0) GO TO 7
      WRITE (6,3004) DISPTON,L,T,GM,BM,TPHI,Q
     GO TO 8
*
    7 WRITE (6,2004) DISPTON,L,T,GM,BM,TPHI,Q
    8 CONTINUE
      READ (5,1000) SHAPE
      WRITE (6,2005) SHAPE
      READ  (5,1004) ISC, ANGLE
      IF(ISC.EQ.0) GO TO 10
      WRITE (6,2006) ANGLE
   10 READ (5,1004) ITERATE
      STAT = 1.0
      PRCN = 0.01
      IF (ITERATE .GT. 0) WRITE (6,2017)
      IF (ITERATE .EQ.0)  READ (5,1002) (DUC(IV,1),IV=1,NV)
      IF (ITERATE .EQ.0)  WRITE (6,2016) (DUC(IV,1),IV=1,NV)
      IF (ITERATE .EQ.0)  GO TO 20
      WRITE (6,2007)
      DO 15 IV=1,NV
       READ(5,1002) (DUC(IV,I),I=1,6)
   15  WRITE(6,2009) VK(IV),(DUC(IV,I),I=1,6)
   20 READ  (5,1000) IPRINT
      IF((ISC.NE.0).AND.(IPRINT(1).EQ.SPECTRA)) GO TO 22
      IF (IPRINT(1) .EQ. SPECTRA) WRITE (6,2018)
      IF (IPRINT(2) .EQ. ITERATN) WRITE (6,2019)
      GO TO 25
   22 WRITE(6,2029)
      GO TO 900
*
*INPUT AND OUTPUT CONDITIONS FOR FIN STABILIZED ROLL PREDICTIONS.
*
   25 READ (5,1001) NSTAB
      IF (NSTAB .LT. 1) GO TO 35
      IF (NSTAB .GE. 1 .AND. IUNITS .EQ. 0)  WRITE (6,2024) NSTAB
      IF (NSTAB .GE. 1 .AND. IUNITS .EQ. 1)  WRITE (6,3024) NSTAB
     DO 28 I=1,NSTAB
      READ (5,1004) M(I),AREA(I),R(I)
      READ (5,1002) DCLDBFS(I),H0(I),H1(I),H2(I),H3(I),H4(I)
      READ (5,1002) GK(I),GV(I),K1(I),K2(I),K3(I)
      READ (5,1002) A1(I),A2(I),A3(I),B1(I),B2(I),B3(I)
   28 WRITE (6,2025) I,M(I),AREA(I),R(I),DCLDBFS(I),H0(I),H1(I),H2(I),
     2 H3(I),H4(I),GK(I),GV(I),K1(I),K2(I),K3(I),A1(I),A2(I),A3(I),
     2 B1(I),B2(I),B3(I)
       READ (5,1001) NSAT
       IF (NSAT.EQ.0) GO TO 30
       READ (5,1002) (BSTOP(IV),BVELMAX(IV),IV = 1,NV)
       DO 29 IV = 1,NV
   29  IF(BVELMAX(IV).EQ.0.0) BVELMAX(IV) = 10.*BSTOP(IV)/TPHI
       WRITE (6,2028) (IV,BSTOP(IV),BVELMAX(IV),IV = 1,NV)
   30  CONTINUE
   35  CONTINUE
*
*INITIALIZE.
```

```
*
      IF  (IUNITS .EQ. 0) GO TO 38
*
      UM = 3.28084
      DO 36 I = 1,NWH
      SWMET(I) = SWH(I)
      SWH(I) = SWH(I)*UM
   36  CONTINUE
      DISPTON = DISPTON*0.9842
      L = L*UM
      T = T*UM
      GM = GM*UM
      BM = BM*UM
*
      IF (NSTAB .LT. 1) GO TO 38
       DO 37 I = 1,NSTAB
      AREA(I) = AREA(I)*10.7639
      R(I) = R(I)*UM
   37  CONTINUE
*
   38 CONTINUE
*
      WPHI=2.*PI/TPHI
      DISPLB = 2240. * DISPTON
      DO 40 IV=1,NV
   40 VFS(IV) = 1.6878* VK(IV)
      TERM1 = 2.*PI*GRAVITY/L
      DO 60 IW=1,NW
      W(IW)=FLOAT(IW)*WDEL
   60 FKT(IW) = EXP (-W(IW)**2/GRAVITY * T)
*
*GENERATE VALUES FOR COSINE SQUARED SPREADING OF WAVE ENERGY.
*
      IF (ISC .EQ. 0) GO TO 75
      HA = (180./ANGLE)/2.
      CON1 = 1./HA
      NNU = 2*IFIX(HA) - 1
      ILC = NNU/2 + 1
      CON2 = PI/(2.*HA)
      J = -IFIX(HA)
      DO 70 I=1,NNU
      J = J + 1
      P(I) = J
   70 COS1(I)   = COS(P(I)*CON2)**2
   75 CONTINUE
*
*BEGIN LOOP OVER SEA CONDITIONS.
*
      DO 700 IWH=1,NWH
*
*COMPUTE BRETSCHNEIDER 2-PARAMETER WAVE SLOPE SPECTRUM.
*
      CALL BRWSSP (NW,SWH(IWH),TO(IWH),W,S)
*
*BEGIN LOOP OVER SHIP SPEED.
*
      DO 600 IV=1,NV
```

```
*
*BEGIN LOOP OVER SHIP HEADING (MU), PREDOMINANT WAVE DIRECTION.
*
      DO 500 IMU=1,NMU
      IF ((IV.EQ.1) .AND. (IWH.EQ.1))
     2 MUR(IMU) = PI/180. * FLOAT(MUD(IMU))
      DAMPU(IMU) = DUC(IV,1)
      IF (ITERATE .EQ.0) GO TO 90
      NTRY = 0
       YP = 0.0
   80  NTRY = NTRY + 1
       X = YP
       DAMPU(IMU) = DUC(IV,1) + 1.61*DUC(IV,2)*X**0.772 + 1.88*DUC(IV,3
     2)*X + 4.00*DUC(IV,4)*X**2.0 + 9.40*DUC(IV,5)*X**3.0 +
     2 24.0*DUC(IV,6)*X**4.0
   90 SIGLC(IMU) = SIGSQSC(IMU) = 0.
       SIGVLC(IMU) = SGVSQSC(IMU) = 0.
*
*BEGIN LOOP OVER SPREADING ANGLE (NU).
*
*(FOR PURELY LONG CRESTED-CASE, NO. OF NU'S = 1, AND NU = MU.)
*
      IF (ISC .EQ. 0) NNU = 1
      DO 400 INU=1,NNU
      NUR(INU) =MUR(IMU)+P(INU)*CON2
      SINNU(INU) = SIN(NUR(INU))
   50 COSNU(INU) = COS(NUR(INU))
*
*BEGIN LOOP OVER WAVE FREQUENCY.
*
      DO 200 IW=1,NW
      KL = L * W(IW)**2 * COSNU(INU) / (2. * GRAVITY)
      SINKL = SIN(KL)
      COSKL = COS(KL)
      WE(IW,INU)=ABS(W(IW)* (1. - W(IW) * VFS(IV) / GRAVITY *
     2 COSNU(INU)))
      TUNF = WE(IW,INU)/WPHI
      BA = 2.*DAMPU(IMU) * TUNF
      A = 1. - TUNF*TUNF
      CA = SQRT(A*A + BA*BA)
*
*TEST FOR WATERPLANE SHAPE.
*
      IF (SHAPE .EQ. ELLIP) GO TO 110
      IF (SHAPE .EQ. RECTANG) GO TO 120
*
*WATERPLANE IS PARABOLIC.
*
      LPRIME = L * .5
      IF (ABS(KL) .GT. EPS) GO TO 105
      F = 1.
      G = 0.
      D = 1.
      GO TO 127
  105 F = 3. * (SINKL - KL * COSKL) / KL**3
      G = 1575. / KL**7 * ((1. - 2. * KL**2 / 5.) * SINKL
     2 - KL * (1. - KL**2 / 15.) * COSKL) - F
```

```
      D = F + BM / GM * G
      GO TO 127
*
*WATERPLANE IS ELLIPTICAL.  (DETERMINE THE ZEROTH AND FIRST BESSEL
*FUNCTIONS OF KL.)
*
  110 LPRIME = SQRT(7.)/4. * L
      IF (ABS(KL) .GT. EPS) GO TO 115
      F = 1.
      G = 0.
      D = 1.
      GO TO 127
  115 CALL BESSJ (KL,0.,1,BESSEL)
      F = 2. / KL * BESSEL(2)
      G = - 8. / KL**2 * BESSEL(1) + (8. / KL**2 - 1.) * F
      D = F + BM / GM * G
      GO TO 127
*
*WATERPLANE IS RECTANGULAR.
*
  120 LPRIME = L
      IF (ABS(KL) .GT. EPS) GO TO 125
      D = 1.
      GO TO 127
  125 D = SINKL / KL
  127 CONTINUE
      KLPRIME = .5 * W(IW)**2 / GRAVITY * LPRIME * COSNU(INU)
      C = SIN(KLPRIME) / KLPRIME
      H = D - Q*C*TUNF*TUNF
*
*COMPUTE ROLL TRANSFER FUNCTION.
*
      TR(IW) = EKT(IW)/CA*SINNU(INU)*SQRT(H*H+C*C*BA*BA)
*
*COMPUTE ROLL SPECTRUM.
*
      SUR(IW,INU)= S(IW)*TR(IW)*TR(IW)
       SURV(IW,INU) = SUR(IW,INU)*WE(IW,INU)*WE(IW,INU)
*
*END OF LOOP OVER WAVE FREQUENCY.
*
  200 CONTINUE
*
*DETERMINE RMS ROLL VALUE.
*
      CALL ALGRNG (NW,W,SUR(1,INU),HOUR(INU))
       CALL ALGRNG(NW,W,SURV(1,INU),VHOUR(INU))
*
* IF REQUESTED COMPUTE LONG-CRESTED VALUES
*
      IF (ISC .NE. 0) GO TO 390
       SIGLC(INU) = SQRT(HOUR(INU))
       SIGVLC(INJ) = SQRT(VHOUR(INJ))
*
* IF REQUESTED, ITERATE OVER ROLL DAMPING FOR LONG-CREST CASE.
*
      IF (ITERATE .EQ. 0) GO TO 400
```

```
      KMU = INU
      KV = IV
      KNU = INU
      SGVONLC = SIGVLC(INU)/WPHI
      PHIN = DAMPU(INU)
      CALL ITREQ(SGVONLC), RETURNS(80,400,900)
*
*BEGIN SUMMING OF SHORTCRESTED RESPONSE DATA.
*
  300 SIGSQSC(INU) = SIGSQSC(INU) + COS1(INU)*W0UR(INU)
       SGVSCSC(INU) = SGVSQSC(INU) + COS1(INU)*VW0UR(INU)
*
$END OF LOOP OVER NU.
*
  400 CONTINUE
*
     IF (ISC .EQ. 0) INU = 1
      IF (ISC .EQ. 0) GO TO 210
      SIGSC(INU) = SQRT(CON1*SIGSQSC(INU))
       SIGVSC(INU) = SQRT(CON1*SGVSQSC(INU))
       SGVONPH = SIGVSC(INU)/WPHI
      KMU=INU
      KNU=INU
      KV=IV
      IF (ITERATE .EQ. 0) GO TO 250
      PHIN=DAMPU(INU)
       CALL ITRE2(SGVONPH), RETURNS(80,250,900)
*
*IF REQUESTED, PRINT LONGCRESTED SPECTRUM AND ITS COMPONENTS.
*
  210 IF (IPRINT(1).NE.SPECTRA) GO TO 250
*
      IF (IUNITS .EQ. 0) GO TO 231
*
      WRITE (6,3010) TITLE2,SWMET(IWH),T0(IWH),VK(IV)
      GO TO 232
*
  231 WRITE (6,2010) TITLE2,SWH(IWH),T0(IWH),VK(IV)
  232 CONTINUE
      WRITE (6,2023) MUD(INU)
       WRITE (6,2020)
      DO 350 IW=1,NW
      PER = 2.*PI/W(IW)
      LAM = PER*PER*GRAVITY/(2.*PI)
      LAMONL = LAM/L
      WN = 360.*W(IW)*W(IW)/(2.*PI*GRAVITY)
      RAO=TR(IW)*TR(IW)
      SD = S(IW)/(WN*WN)
      RAOD = WN*WN*RAO
      SURD = SD * RAOD
      WRITE (6,2021) W(IW),WE(IW,INU),LAM,LAMONL,WN,TR(IW),RAO,S(IW),
     2 SUR(IW),     RAOD,SD,SURD
  350 CONTINUE
      WRITE (6,2022) SIGLC(INU)
*
*IF REQUESTED, COMPUTE STABILIZED ROLL AND FIN MOTIONS FOR THIS
*PREDOMINANT HEADING.
```

```
*
  250  IF (NSTAB .LT. 1) GO TO 500
       DO 280 IS=1,NSTAB
       CALL FINSTAB (IS), RETURNS (280,900)
  280  CONTINUE
*
$END OF LOOP OVER PREDOMINANT HEADING.
*
  500  CONTINUE
*
*ONLY LONGCRESTED ROLL VALUES ARE OUTPUT.
*
       IF (IUNITS .EQ. 0) GO TO 502
*
       WRITE (6,3010) TITLE2,SWMET(IWH),T0(IWH),VK(IV)
       GO TO 503
*
  502  WRITE(6,2010) TITLE2,SWH(IWH),T0(IWH),VK(IV)
  503  CONTINUE
       WRITE(1) TITLE2,SWH(IWH),T0(IWH),VK(IWH)
       IF (ISC .NE. 0) GO TO 550
       IF (ITERATE .EQ. 0) WRITE(6,2030)
       WRITE(6,2031)
       DO 505 IMU = 1,NMU
  505  WRITE(6,2014) MUD(IMU),DAMPU(IMU),SIGLC(IMU)
       WRITE(1) (SIGLC(IMU),IMU = 1,NMU)
       IF (NSTAB .EQ. 0) GO TO 600
       DO 540 I = 1,NSTAB
       WRITE(6,2032) I
       DO 525 IMU = 1,NMU
  525  WRITE(6,2014) MUD(IMU),DAMPS(I,IMU),SSIGLC(I,IMU),ITEST(I,IMU),
     2 BMOTLC(I,IMU),BVELLC(I,IMU)
       WRITE(1) (SSIGLC(I,IMU), IMU = 1,NMU)
  540  CONTINUE
       IF (NSAT .EQ. 0) GO TO 600
       WRITE(6,2222)
       GO TO 600
*
*ONLY SHORTCRESTED ROLL VALUES ARE OUTPUT
*
  550  IF(ITERATE .EQ. 0) WRITE(6,2030)
       WRITE(6,2013)
       DO 555 IMU = 1,NMU
  555  WRITE(6,2014) MUD(IMU),DAMPU(IMU),SIGSC(IMU)
       WRITE(1) (SIGSC(IMU),IMU = 1,NMU)
       IF (NSTAB .EQ. 0) GO TO 600
       DO 590 I = 1,NSTAB
       WRITE(6,2026) I
       DO 575 IMU = 1,NMU
  575  WRITE(6,2014) MUD(IMU),DAMPS(I,IMU),SSIGSC(I,IMU),ITEST(I,IMU),
     2 BMOTSC(I,IMU),BVELSC(I,IMU)
       WRITE(1) (SSIGSC(I,IMU),IMU = 1,NMU)
  590  CONTINUE
       IF (NSAT .EQ. 0) GO TO 600
       WRITE(6,2222)
$
$END OF LOOP OVER SPEED.
```

```
      $
        600  CONTINUE
      *
      $END OF LOOP OVER SEA CONDITION.
      *
        700  CONTINUE
        900  WRITE (6,2015)
      *
             STOP
       1000  FORMAT (8A10)
       1001  FORMAT (16I5)
       1002  FORMAT (8F10.6)
       1004  FORMAT (I5,2F10.5,A10)
       2000  FORMAT (1H1,27(/),45X,42H* * * ROLL MOTION PREDICTION PROGRAM * *
            2 *///,56X,3A10)
       2001  FORMAT (1H1,8A10///)
       2002  FORMAT (1X,*SIGNIFICANT WAVE HEIGHT(S) (FEET) =*,5X,10F7.2)
       2003  FORMAT (1X,*MODAL WAVE PERIOD(S) (SECONDS) =*,8X,10F7.2//)
       2004  FORMAT(/1X,*DISPLACEMENT (L. TONS) =*16X,F7.0/1X *LENGTH BETWEEN
            2PP (FEET) =*14X,F7.1/1X,*DRAFT (FEET) =* 26X,F7.2/1X,
            2*TRANSVERSE METACENTRIC HEIGHT (FEET) =*2X,F7.1/1X*METACENTER ABOV
            2E BUOYANCY CENTER (FT) =*,1X,F7.2/1X,*ROLL PERIOD (SECONDS) =*,17X
            2,F7.2/1X, *Q =*,37X,F7.3)
       2005  FORMAT (1X,*WATERPLANE SHAPE =*,24X,A10)
       2006  FORMAT (1X,*SPREADING ANGLE =*23X,F7.0//)
       2007   FORMAT(1X,110HDAMPING INPUT IN THE FORM  N = C1 + 1.61*C2*Y**0.7
            272 + 1.88*C3*Y + 4.00*C4*Y**2 + 9.40*C5*Y**3 + 24.00*C6*Y**4//
            2* SPEED (KNOTS)*,4X,*C1*,7X,*C2*,7X,*C3*,7X,*C4*,7X,*C5*,7X,*C6*)
       2008  FORMAT (1X,*SHIP SPEED(S) (KNOTS) =*,19X,9F5.1/)
       2009   FORMAT(4X,F5.1,2X,6(2X,F7.4))
       2010  FORMAT (1H1,8A10//1X,*SIGNIFICANT WAVE HEIGHT =*F7.2,* FEET*
            2 / 1X                                                        *MODA
            2L WAVE PERIOD =*F7.2* SECONDS*/1X*SHIP SPEED =*  F5.1,* KNOTS*)
       2011  FORMAT (//1X,*UNSTABILIZED RMS ROLL (DEGREES)*/1X,*HEADING*7X*LC*
            2 8X,*SC*/)
       2012  FORMAT (I6,1X,2F10.2,2X,A1,15X,2F10.2,12X,2F10.2)
       2013  FORMAT (//1X,*UNSTABILIZED RMS ROLL (DEGREES)*/ 1X,*HEADING* 8X,
            2 *N*8X*SC*/)
       2014  FORMAT (I6,1X,F10.4,F10.2,2X,A1,25X,F10.2,22X,F10.2)
       2015  FORMAT (1H1,27(/),57X,17H* * * E N D * * *)
       2016  FORMAT (1X,*ROLL DAMPING COEFFICIENT(S) =*,13X,5F5.3///)
       2017  FORMAT (1X,*ITERATION OVER ROLL DAMPING WILL BE DONE.*/)
       2018  FORMAT (//1X,*LONGCRESTED SPECTRA AND COMPONENTS WILL BE PRINTED.
            2*)
       2019  FORMAT (//1X,*INTERMEDIATE STEPS IN ROLL DAMPING ITERATION WILL B
            2E PRINTED.*)
       2020  FORMAT (//9X,*W*,8X,*WE*,7X,*LAM*,5X,        *LAM/L*,9X,*K*,8X,
            2 *TR*,7X,*RAO*,4X,*W SL S*,7X,*SUR*, 3X,*RAO DIM*,4X,*W HT S*,3X,
            2 *SUR DIM*/  3X,*RAD/SEC*3X *RAD/SEC*8X,*FT*,17X,*DEG*,3X,*DEG/DEG
            2 DEG/DEG SQ DEGSQ SEC*1X,*DEGSQ SEC*,1X,*DEG/FT SQ*1X,*FTSQ SEC*1X
            2 *DEGSQ SEC*)
       2021  FORMAT (12F10.3)
       2022  FORMAT (//1X,*RMS ROLL =*F7.2* DEGREES*)
       2023  FORMAT (//1X,*SHIP HEADING =*I3* DEGREES*)
       2024  FORMAT (//1X,*ROLL STABILIZATION WILL BE CALCULATED FOR *I3
            2 * CASES*// 1X *FIN AND CONTROL SYSTEM PARAMETERS ARE AS FOLLOWS:*
            2 //* CASE* 2X *M* 6X *A* 5X *R  (DCL/DB)FS* 4X *H0* 4X *H1* 4X
```

```
     2 *H2* 4X *H3* 4X *H4* 4X *GK* 4X *GV* 4X *K1* 4X *K2* 4X *K3* 4X
     2 *A1* 4X *A2* 4X *A3* 4X *B1* 4X *B2* 4X *B3* /10X *FT SQ* 4X *FT*
     2 4X *PER DEG*/)
2025  FORMAT (I5,I3,F7.2,F6.2,F12.3,16F6.3)
2026  FORMAT (//1X,*CASE*I3,*:  STABILIZED RMS ROLL (DEGREES)*
     2 10X,*FIN MOTION (DEGREES)* 10X *FIN VELOCITY (DEGREES/SECOND)*/
     2 1X,*HEADING* 8X *N* 8X *SC* 36X*SC* 30X *SC*/)
2027  FORMAT (//1X,*CASE*I3,*:  STABILIZED RMS ROLL (DEGREES)*
     2 10X,*FIN MOTION (DEGREES)* 10X *FIN VELOCITY (DEGREES/SECOND)*/
     2 1X,*HEADING* 7X *LC* 8X *SC* 27X *LC* 9X *SC* 19X *LC* 8X *SC*/)
2028   FORMAT (//5X,*IV*5X,*BSTOP*5X,*BVELMAX*/,
     2  (I7,2X,F10.5,2X,F10.5,/))
2029  FORMAT(//1X,*NO SPECTRA OUTPUT ALLOWED IN SHORTCRESTED CASE. REV
     2ISE YOUR INPUT DATA.*)
2030  FORMAT(//1X,*ITERATION OVER ROLL-DAMPING NOT PERFORMED.*)
2031  FORMAT(//1X,*UNSTABILIZED RMS ROLL (DEGREES)*/1X,*HEADING*,8X,
     2 *N*,8X,*LC*/)
2032  FORMAT(//1X,*CASE*I3,*:  STABILIZED RMS ROLL (DEGREES)*
     2 10X,*FIN MOTION (DEGREES)*,10X,*FIN VELOCITY (DEGREES/SECOND)*/
     2 1X,*HEADING* 8X *N* 8X *LC* 36X *LC* 30X *LC*/)
2222  FORMAT(//1X,36H* SATURATION FACTOR IS INSIGNIFICANT)
3002  FORMAT (1X,*SIGNIFICANT WAVE HEIGHT(S) (METERS) =*,3X,10F7.2)
3004  FORMAT(/1X,*DISPLACEMENT (M. TONS) =*23X,F7.0/1X *LENGTH BETWEEN
     2PP (METERS) =*14X,F7.1/1X,*DRAFT (METERS) =* 26X,F7.2/1X,
     2*TRANSVERSE METACENTRIC HEIGHT (METERS) =*2X,F7.1/1X*METACENTER AB
     2OVE BUOYANCY CENTER (M) =*,4X,F7.2/1X,*ROLL PERIOD (SECONDS) =*,
     219X,F7.2/1X, *Q =*,39X,F7.3)
3010  FORMAT (1H1,8A10//1X,*SIGNIFICANT WAVE HEIGHT =*F7.2,* METERS*
     2 / 1X                                                        *MODA
     2L WAVE PERIOD =*F7.2* SECONDS*/1X*SHIP SPEED =*  F5.1,* KNOTS*)
3024  FORMAT (//1X,*ROLL STABILIZATION WILL BE CALCULATED FOR *I3
     2 * CASES*// 1X *FIN AND CONTROL SYSTEM PARAMETERS ARE AS FOLLOWS:*
     2 //* CASE* 2X *M* 4X *A* 7X *R  (DCL/DB)FS* 4X *H0* 4X *H1* 4X
     2 *H2* 4X *H3* 4X *H4* 4X *GK* 4X *GV* 4X *K1* 4X *K2* 4X *K3* 4X
     2 *A1* 4X *A2* 4X *A3* 4X *B1* 4X *B2* 4X *B3* /11X *M SQ* 5X *M *
     2 3X *PER DEG*/)
      END
```

```
      SUBROUTINE ITREQ(SIG),RETURNS(A,B,C)
      COMMON/ITRTN/STAT,PRCN,NTRY,IMU,INU,IV,GP,GPM1,YPM1,YP,YPP1,
     2 PHIN,IPRINT(8),ITERATE,WPHI
      DATA ITERATN/7HITERATN/
      IF (NTRY.GT.10) WRITE(6,4998)
      IF (NTRY .GT. 10) RETURN C
      IF((IPRINT(2) .EQ.ITERATN) .AND. (IMU .EQ. 1) .AND. (NTRY.EQ.1))
     2 WRITE(6,8101)
      GP = STAT*SIG
      IF (IPRINT(2) .EQ. ITERATN) WRITE(6,8100)IV,IMU,NTRY,PHIN,YPP1,
     2 YP,YPM1,GP,GPM1
      IF (GP .LT. .01) RETURN B
      IF (NTRY .EQ. 1) GO TO 20
      IF (ABS(1 - GP/YP) .LE. PRCN) RETURN B
      YPP1 = (GPM1*YP - GP*YPM1)/((YP - YPM1) - (GP - GPM1))
      YPM1 = YP
      GPM1 = GP
      YP = YPP1
      IF (IPRINT(2) .EQ. ITERATN) WRITE(6,8100)IV,IMU,NTRY,PHIN,YPP1,
     2 YP,YPM1,GP,GPM1
      RETURN A
   20 GPM1 = GP
      YPM1 = 0.0
      YP = GP/2.0
      IF (IPRINT(2) .EQ. ITERATN) WRITE(6,8100)IV,IMU,NTRY,PHIN,YPP1,
     2 YP,YPM1,GP,GPM1
      RETURN A
 4998 FORMAT(1H * - - - - - PROGRAM STOPPED BECAUSE ROLL FAILED TO CONV
     2ERGE WITHIN 10 ITERATIONS - - - - - *)
 8100 FORMAT(1X,3I5,6F10.3)
 8101 FORMAT(//,3X,*IV*,3X,*IMU*,2X,*NTRY*,4X,*PHIN*,6X,*YP+1*,7X,*YP*
     2,7X,*YP-1*,7X,*GP*,7X,*GP-1*/)
      END
```

```
      SUBROUTINE BRWSSP (N,SIGWH,TMODAL,W,S)
C=======================================================================
C     COMPUTES BRETSCHNEIDER WAVE SLOPE SPECTRUM
      REAL K
      DIMENSION W(N),S(N)
      DATA A,B,PI,G /487.0626,1948.2444,3.1415927,32.1725/
C     ( TMODAL = 2.76 * SIGWH**.5 )
      TMODAL4 = TMODAL**4
C=======================================================================
C     FOR PIERSON-MOSKOWITZ SPECTRA -    TMODAL**4 = 58.0936 * SIGWH**2
      CON1 = A * SIGWH**2 / TMODAL4
      CON2 = B / TMODAL4
      DO 10 I=1,N
      W4 = W(I)**4
      W5 = W(I) * W4
      ARG = CON2 / W4
      IF (ARG .GT. 500.) S(I) = 0.
      IF (ARG .GT. 500.) GO TO 10
C=======================================================================
C     BRETSCHNEIDER WAVE HEIGHT SPECTRUM
      S(I) = CON1/W5 * EXP(-ARG)
C=======================================================================
C     WAVE NUMBER IN DEGREES
      K = 360.*W(I)*W(I) / (2.*PI*G)
C=======================================================================
C     BRETSCHNEIDER WAVE SLOPE SPECTRUM
      S(I) = K*K * S(I)
   10 CONTINUE
      RETURN
      END
```

```
C
C------VERSION 3  -  CDC 6700  -  A L G R N G  -  JANUARY, 1974---------
C------S. BALES----------------------------------------------------------
C
      SUBROUTINE ALGRNG (N,W,S,AREA)
*
*THIS SUBROUTINE COMPUTES THE AREA UNDER THE CURVE FOR A PARTICULAR
*SPECTRUM.  AN ODD NUMBER OF POINTS (FREQUENCIES) SHOULD BE USED.-------
*
     INTEGER ERROR
      DIMENSION W(N),S(N)
      DATA ITAG/0/
      DATA EPS/0.0000000001/
C
      ERROR = 10
      IF (ERROR .EQ. 10) ITAG = 0
     ERROR=0
      W0=W(1)-.03
      AREA0 = 0.5*S(1)*(W(1) -W0)
     MN=N-2
     AREA=0.
      TEMP = 0.
      AREA2 = AREA3 = 0.
      NOMEGA =  MOD(N,2)
     DO 20 M=1,MN,2
     A=W(M+2)-W(M)
     B=W(M+2)-W(M+1)
     C=W(M+1)-W(M)
      PAREA = A*A/6.*(S(M)*(3.*C-A)/(A*C)+S(M+1)*A/(B*C)+
    2 S(M+2)*(2.*A-3.*C)/(A*B))
      TEMP = PAREA
      IF (PAREA .LT. 0.) TEMP = 0.
      AREA = AREA + TEMP
      IF (PAREA .GE. 0.) GO TO 20
     IF(-PAREA.GT.0.10*AREA) ERROR=1
20     CONTINUE
      PAREA = 0.
      IF (AREA .LE. 0.000010) GO TO 100
C
C------SEARCH FOR SPECTRAL CLOSURE---------------------------------------
C
      TEMP = 0.
      SMAX = S(1)
      ITEST = 1
      DO 30 I=2,N
   30 IF (S(I) .GT. SMAX) SMAX = S(I)
      X10PRCN = 0.10*SMAX
   50 ITEST = ITEST +1
      IF (ITEST .EQ. 2) J=1
      IF (ITEST .EQ. 3) J=N
      IF ((SMAX-S(J)) .LE. EPS   ) ERROR = ITEST
      IF((ERROR .EQ. 2) .OR. (ERROR .EQ.3)) ITAG = 1
      IF((ERROR .EQ. 2) .AND. (ITEST .EQ. 2)) TEMP=AREA+AREA0
      IF((ERROR .EQ. 2) .AND. (ITEST .EQ. 2)) AREA=TEMP
      IF (S(J) .GT. X10PRCN) ERROR = ITEST + 2
      IF ((ERROR .GT. 0) .AND. (ITAG .EQ.0)) ITAG = 1
      IF ((J .EQ. N) .AND. (ERROR.EQ. 4)) GO TO 107
```

```
              IF ((J .EQ. N) .AND. (ERROR .LT. 5)) GO TO 100              ALGR
              IF ((ERROR .EQ.4) .OR. (ERROR .EQ. 5))GO TO 60              ALGR
              IF (ITEST .LT. 3) GO TO 50                                  ALGR
              GO TO 100                                                   ALGR
        C                                                                 ALGR
        C------DRAW A STRAIGHT LINE THRU FIRST (LAST) TWO SPECTRAL VALUES ALGR
        C------TO THE ABSCISSA AND ADD ON AREA FOR CLOSURE AT LOW (HIGH)  ALGR
        C------FREQUENCY END.-------------------------------------------- ALGR
        C                                                                 ALGR
           60 IF ((ERROR.EQ.5) .AND.  (S(J).GE. S(J-1)))GO TO 75          ALGR
              IF ((ERROR.EQ.4) .AND.  (S(1).GE. S(2  )))GO TO 50          ALGR
              IF (ERROR .EQ. 4) J=2                                       ALGR
              IF (ERROR .EQ. 5) J=N                                       ALGR
              SLOPE = (S(J-1) - S(J))/(W(J-1) - W(J))                     ALGR
              IF(SLOPE .LE.0.) GO TO 70                                   ALGR
              SLOPE = AMIN1(-SLOPE,-1.0)                                  ALGR
           70 IF (J .EQ. 2) J = 1                                         ALGR
              ANEW = -0.5 * S(J)**2 / SLOPE                               ALGR
              IF (ERROR .EQ. 4) AREA2 = AMIN1(AREA0,ANEW)                 ALGR
              IF (ERROR .EQ. 5) AREA3 = ANEW                              ALGR
           75 TEMP = AREA + AREA2 + AREA3                                 ALGR
              IF (J .LT. N) GO TO 50                                      ALGR
          107 TEMP = AREA + AREA2 + AREA3                                 ALGR
              AREA = TEMP                                                 ALGR
          100 RETURN                                                      ALGR
        C                                                                 ALGR
             END                                                          ALGR
```

```
      SUBROUTINE FINSTAB (IS), RETURNS (AAA,988)
*
*SUBROUTINE TO PREDICT STABILIZED (FIN) ROLL MOTION USING CONOLLY AND
*COX.
*
      REAL MM,KK1,KK2,KK3,KR,KI,K1,K2,K3
       COMMON/ITRTN/STAT,PRCN,NTRY,IMU,KNU,IV,GP,GPM1,YPM1,YP,YPP1,
     2 PHIN,IPRINT(8),ITERATE,NPHI
      COMMON /STAB/ NSTAB,M(10),AREA(10),R(10),DCLDBFS(10),H0(10),
     2 H1(10),H2(10),H3(10),H4(10),GK(10),GV(10),K1(10),K2(10),K3(10),
     2 A1(10),A2(10),A3(10),B1(10),B2(10),B3(10),DAMPU(13),DAMPS(10,13),
     2  DUC(5,6),SSIGLC(10,13),NNU,ILC,ISC,WE(40,35),
     2  SSIGVLC(10,13),SSIGVSC(10,13),
     2 SUR(40,35),W(40),NW,COS1(35),CON1,SSIGSC(10,13),
     2 VFS(5),DISPLB,GM , BMOTLC(10,13),
     2  BMOTSC(10,13),BVELSC(10,13),BVELLC(10,13),BSTOP(5),BVELMAX(5)
     2  ,NSAT,ITEST(10,13)
      DIMENSION SMOUR(35),SSU(40,35),FINM(40,35),FINV(40,35),BMOUR(35),
     2  BVMOUR(35),SSV(40,35),SVMOUR(35)
       DATA RHO/1.99/ , PI/3.1415926/
*
*INITIALIZE.
*
      N=IS
      MM=M(N)
      AAREA=AREA(N)
      RR=R(N)
      DDCLDBF=DCLDBFS(N)
      HH0=H0(N)
      HH1=H1(N)
      HH2=H2(N)
      HH3=H3(N)
      HH4=H4(N)
      GGK=GK(N)
      GGV=GV(N)
      KK1=K1(N)
      KK2=K2(N)
      KK3=K3(N)
      AA1=A1(N)
      AA2=A2(N)
      AA3=A3(N)
      BB1=B1(N)
      BB2=B2(N)
      BB3=B3(N)
      CON3=RHO*VFS(IV)*VFS(IV)*MM*AAREA*RR/(DISPLB*GM)
       SSM = 1.0
       ISOK = 0
   75  DAMPS(N,IMU) = DUC(IV,1)
      IF (ITERATE .EQ. 0) GO TO 90
      NTRY = 0
       YP = 0.0
   80  NTRY = NTRY + 1
       X = YP
       DAMPS(N,IMU) = DUC(IV,1)+1.61*DUC(IV,2)*X**0.772 + 1.88*DUC(IV,3
    2)*X + 4.00*DUC(IV,4)*X**2.0 + 9.40*DUC(IV,5)*X**3.0 +
     2  24.0*DUC(IV,6)*X**4.0
   90  PHIS = SSIGVLC(N,IMU) = SSIGVSC(N,IMU) = 0.
```

```
      BMOTSC(N,IMU)=BVELSC(N,IMU)=BMOTLC(N,IMU)=BVELLC(N,IMU) = 0.
*
*BEGIN LOOP OVER SPREADING ANGLE (NU).
*
      IF (ISC .EQ. 0) NNU = 1
       DO 400 INU = 1,NNU
*
*BEGIN LOOP OVER WAVE FREQUENCY.
*
      DO 200 IW=1,NW
      WWE=WE(IW,INU)
      WESQ=WWE*WWE
      TUNF = WE(IW,INU)/WPHI
      BA = 2.*DAMPU(IMU)*TUNF
      A = 1. - TUNF*TUNF
      CA = SQRT(A*A + BA*BA)
*
*COMPUTE EFFECTIVE LIFT CURVE SLOPE.
*
      DCLOBE = HH0 + HH1*WWE + HH2*WESQ + HH3*WESQ*WWE + HH4*WESQ*WESQ
      DCLOBE = DCLOBE*DOCLOBF*180./3.1415926
*
*COMPUTE AMPLITUDE OF FIN ANGLE TO STABILIZED ROLL.
*
      KR = KK1 - WESQ*KK3
      KI = WWE*KK2
      BR = BB1 - WESQ*BB3
      BI = WWE*BB2
      CON4=KR*KR + KI*KI
      CON5 = BR*BR + BI*BI
      BAONS = GGK*GGV*SQRT(CON4/CON5)
*
      AR = AA1 - WESQ*AA3
      AI = WWE*AA2
*
      BS = 2.*DAMPS(N,IMU)*TUNF
      CS = SQRT(A*A + BS*BS)
      CON6 = AR*BR - AI*BI
      CON7 = AR*BI + AI*BR
      CON8 = AR*AR + AI*AI
       SAONCSP = SSH*CON3*DCLOBE*BAONS/(CS*SQRT(CON8))
*
       COSKSI = (KR*CON6 + KI*CON7)/SQRT(CON4*CON8*CON5)
      SINKSI = (KI*CON6 - KR*CON7)/SQRT(CON4*CON8*CON5)
*
*COMPUTE ROLL REDUCTION FACTOR FOR THIS FREQUENCY.
*
      SONU = CA/CS/SQRT(1.+2.*SAONCSP*((A*COSKSI+
     2 BS*SINKSI)/CS)+SAONCSP*SAONCSP)
*
*COMPUTE STABILIZED ROLL , FIN MOTION, AND FIN VELOCITY SPECTRA.
*
      SSU(IW,INU) = SUR(IW,INU) * SONU * SONU
       SSV(IW,INU) = SSU(IW,INU)*WESQ
      FINM(IW,INU) = SSU(IW,INU) * BAONS * BAONS / CON8
      FINV(IW,INU) = FINM(IW,INU) * WESQ
*
```

```
$END OF LOOP OVER WAVE FREQUENCY.
*
  200  CONTINUE
*
*DETERMINE RMS ROLL, FIN MOTION, AND FIN VELOCITY VALUES.
*
      CALL ALGRNG (NW,W,SSU(1,IMU),SM0UR(IMU))
       CALL ALGRNG(NW,W,SSV(1,IMU),SVM0UR(IMU))
      CALL ALGRNG (NW,W,FINM(1,IMU),BM0UR(IMU))
      CALL ALGRNG (NW,W,FINV(1,IMU),BVM0UR(IMU))
*
*STORE LONGCRESTED VALUES (NO ITERATION OVER ROLL DAMPING IS DONE).
*
      IF (ISC .NE. 0) GO TO 210
      SSIGLC(N,IMU) = SQRT(SM0UR(IMU))
      SSIGVLC(N,IMU)=SQRT(SVM0UR(IMU))
      BMOTLC(N,IMU) = SQRT(BM0UR(IMU))
      BVELLC(N,IMU) = SQRT(BVM0UR(IMU))
      IF (ITERATE .EQ. 0) GO TO 400
      SSGVWLC = SSIGVLC(N,IMU)/WPHI
      PHIN = DAMPS(N,IMU)
      CALL ITREQ(SSGVWLC), RETURNS(80,400,900)
*
*BEGIN SUMMING OF SHORTCRESTED RESPONSE DATA.
*
  210 PHIS = PHIS + COS1(IMU)*SM0UR(IMU)
       SSIGVSC(N,IMU) = SSIGVSC(N,IMU) + COS1(IMU)*SVM0UR(IMU)
      BMOTSC(N,IMU) = BMOTSC(N,IMU) + COS1(IMU)*BM0UR(IMU)
      BVELSC(N,IMU) = BVELSC(N,IMU) + COS1(IMU)*BVM0UR(IMU)
*
$END OF LOOP OVER NU.
*
  400 CONTINUE
      IF (ISC .EQ. 0) GO TO 800
      PHIS = SQRT(CON1*PHIS)
       SSIGVSC(N,IMU) = SQRT(CON1*SSIGVSC(N,IMU))
      BMOTSC(N,IMU) = SQRT(CON1*BMOTSC(N,IMU))
      BVELSC(N,IMU) = SQRT(CON1*BVELSC(N,IMU))
      IF (ITERATE .EQ. 0) GO TO 250
       SSGVOW = SSIGVSC(N,IMU)/WPHI
      PHIN = DAMPS(N,IMU)
       CALL ITREQ(SSGVOW), RETURNS(80,250,900)
  250 SSIGSC(N,IMU) = PHIS
       IF ((NSAT.EQ.0) .OR. (ISOK.EQ.1)) GO TO 800
     X1 = (BSTOP(IV)/BVELMAX(IV))*(BVELSC(N,IMU)/BMOTSC(N,IMU))
     X2 = SIN(X1)
     F = (4/PI)*(X2/X1)
     Y = BSTOP(IV)/(BMOTSC(N,IMU)*1.41421)
       SSM = 1/(1 - X2)*((1 - F*X2)*ERRF(Y) + (F - 1)*X2*ERRF(Y/X2))
       IF (SSM .GE. .98) GO TO 870
       ISOK = 1
       GO TO 75
  870 ITEST(N,IMU) = 1H*
  800 RETURN AAA
  900 RETURN BBB
      END
```

```
FUNCTION ERRF        74/74    OPT=0 ROUND=*/ TRACE            FTN 4.6+460         11/26/79  11.25.38

      C
            REAL FUNCTION ERRF(X)
            DATA    P/.47047/  ,C1/.34802/  ,C2/-.09588/  ,C3/.74786/
              IF (ABS(X) .GT. 15.) GO TO 5
            T = 1/(1 + P*X)
      C
            ERRF = 1 - (C1*T + C2*T*T + C3*T*T*T)*EXP(-X*X)
      C
              GO TO 10
          5   ERRF = 1.
         10  RETURN
            END
```

APPENDIX C

SPECIAL ALGORITHMS

ITERATION OVER ROLL-ROLL DAMPING EQUATIONS*

If roll damping coefficient n is independent of roll angle (as, for example, in some cases where bilge keels are not appended to the hull), FINCON executes with a unique value of n for each required ship speed. However, as has often been found through model experiments, roll damping is dependent on roll angle, as well as ship speed and natural roll frequency. Thus, the program requires a different input description of roll damping. As described in the section of this report entitled Program Input, n is, in this case, defined by

$$n_{IR} = d_o + 1.61\ d_q y^{0.772} + 1.88 d_1 y + 4 d_2 y^2 + 9.4 d_3 y^3 + 24 d_4 y^4 \qquad (7)$$

where $y = \sigma_{\dot{\phi}}/\omega_\phi$ and the fractional power q = 0.772 arises from the turbulent skin friction contribution.

Thus, the computational problem is then to solve the roll equation of motion involving $\dot{\phi}$ for the correct value of n_{IR}.** This has been accomplished by finding the intersection of the known curve of Equation (7) (i.e., $n_{IR} = f(y)$ where $y = \sigma_{\dot{\phi}}/\omega_\phi$) and the initially unknown curve g = $g(n_{IR})$, which is computed from the solution of the roll-rate equation of motion, using the roll damping value n_{IR}.

The solution is found, in brief, by the following procedure as applied to the example of Figure 4:

1. Assume $y_o = 0$, determine $n_o = f(0)$
2. Using n_o, solve the roll-rate equation of motion for

$$g_o = \frac{\sigma_{\dot{\phi}}}{\omega_\phi} = g(n_o)$$

---

*Taken from future report already under preparation by Cox.

**The subscript IR is used here since it is assumed that motion is taking place in irregular waves.

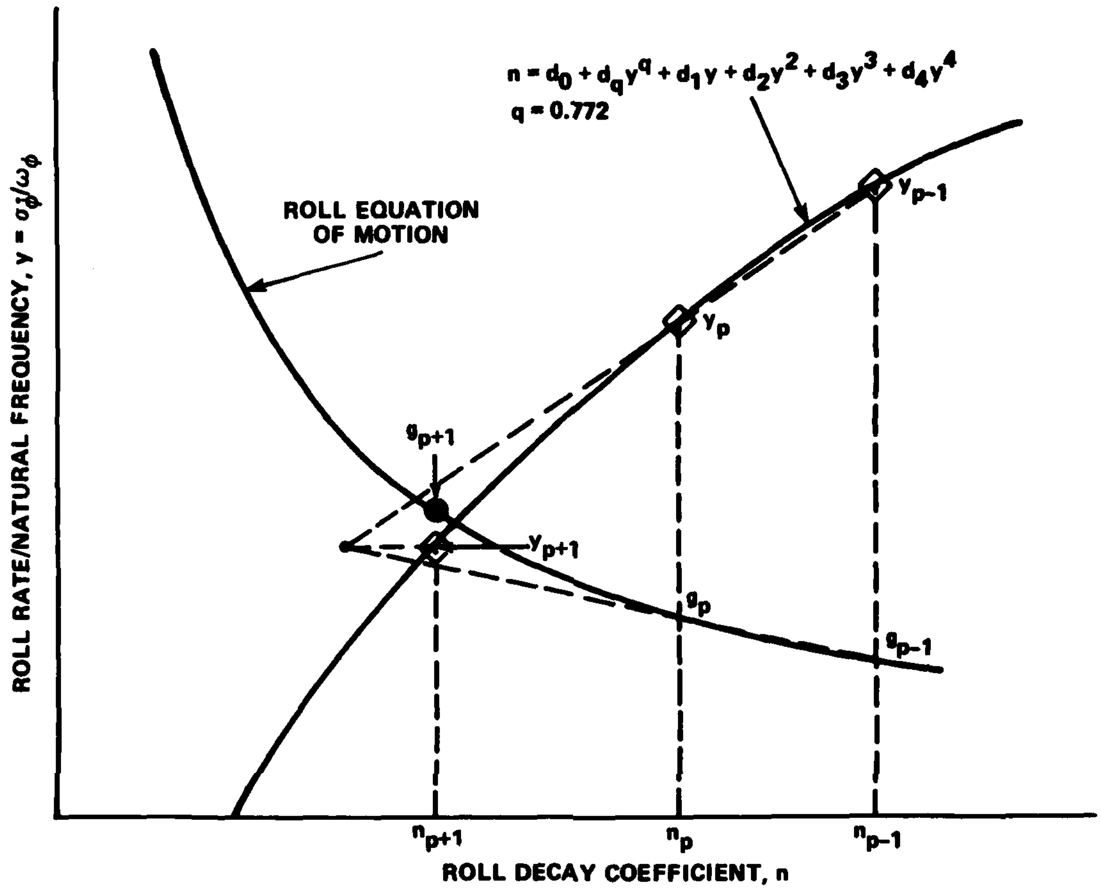

Figure 4 - Illustration of Iteration over Nonlinear Roll-Roll Damping

3. Assume $y_1 = g_o/2$, and determine $n_1 = f(y_1)$
4. Compute $g_1 = g(n_1)$
5. For p = 2, 3, 4 ... etc.
   Calculate $y_p = (g_{p-2}y_{p-1} - g_{p-1}y_{p-2})/[(y_{p-1} - y_{p-2}) - (g_{p-1} - g_{p-2})]$
   and determine $n_p = f(y_p)$
6. Compute $g_p = g(n_p)$ and test if $|1 - g_p/y_p| \leq \varepsilon$ where ε is some small number. If the test is not satisfied, proceed to the next

step of the iteration. If the test is satisfied, then the iteration is terminated and n_p, g_p is the required solution.

In FINCON, ε is usually taken as 0.01 and is called PRCN in the program itself. This means convergence is attained when $|1 - g_p/y_p| \leq 0.01$. Table 6 provides a typical printout of the steps when 1PRINT(2) is input as ITERATN. IV indicates the speed, such as the first; IMU indicates the heading, such as the seventh or 90 degrees; NTRY indicates the numbers of attempts; PHIN indicates the latest selected n value; YP+1 the latest calculated roll-rate value (divided by ω_ϕ); and g_{p-1}, y_{p-1}, g_{p-2}, and y_{p-2} are the previous calculated roll-rate values (divided by ω_ϕ), going back in time. It should be noted that the printing occurs at various steps within each repetition of the iteration rather than just at the end (or beginning) of each attempt. In the particular case listed in Table 6, the first seven lines refer to the unstabilized case, while the last five refer to the stabilized case. Also, it is recalled that the iteration is operating over either the long-crested or short-crested RMS roll rate. A similar procedure, implemented in the Navy Standard Ship Motion Program (SMP-79) (six-degrees-of-freedom) operates over the resonant region of the (long-crested) roll transfer function. Also, the roll-rate values actually used here for the internal testing (e.g., in step 5 above) are usually taken to be the statistic which corresponds to the experimental data described by Equation (7). In all cases, the RMS, single-amplitude roll rate is used. The second page of Table 4 provides a further illustration of this example.

GENERALIZATION OF COSINE SQUARED LAW FOR SHORT-CRESTED SEAS

In general, a 15-degree cosine square spreading function about $\pm$ 90 degrees is used for calculation of ship motions in short-crested or multidirectional seas (e.g., see Reference 3). However, it has been found in calculations done previously, that a more refined angular spread may be required for roll-motion calculations at higher ship speeds. This is due to the highly tuned nature of roll motion. That is, when considering RMS

roll motion across all ship he ·· ·· at high speeds, the maximum values may occur in between the standard 15-degree increments of heading; and, if not considered, some loss of energy may be noticed.

Therefore, a FINCON program option is available for varying the spreading angle used. Spreading angles of 5, 10, or 15 degrees may be specified on data card 9. Though the spreading is thus varied, the predominant heading angles are never varied from the usual 15-degree increments. Table 4 presents results when a 15-degree spreading is specified. In general, either a 15-degree spreading (e.g., for lower speeds) or a 5-degree spreading (e.g., for higher speeds) is recommended; although no specific guidelines for the use of either are currently available. A major difference between the two angles is, of course, in program run time and, thus, in cost. A typical 15-degree spreading run may cost as much as 68 percent less than a 5-degree run. In general, 10-degree spreadings are not recommended, because irregular trends across ship headings may be perceived. For example, for a 75-degree predominant direction, the 10-degree spreading angles are at -15, -5, 5, . . ., 155, 165 degrees; and, for a 90-degree predominant heading, they are at 0, 10, 20, . . ., 165, 180 degrees; while for 105 degrees they are at 15, 25, 35, . . ., 185, 195 degrees. If roll is highly tuned, then adjacent short-crested RMS roll angles may appear to have erratic behavior (e.g., decrease at 75 degrees, increase at 90 degrees, decrease at 105 degrees, etc.). This is due, numerically, just to the difference in the base spreading angles in each case.

The algorithm implemented in FINCON to provide this generalization in the short-cresting procedure is defined by the following:

1. Let I be the specified spreading angle (5, 10, or 15 degrees) or angle of constant energy
2. Set $\ell = (180/I)/2$ and $c = 1/\ell$
3. Then,

$$\sigma^2_{sc}\,(\mu) = c \sum_{p=-(\ell-1)}^{(\ell-1)} \sigma^2_{\ell cn}\left(\mu + \frac{p\pi}{I}\right) \cos^2 \frac{p\pi}{I}$$

where $\sigma^2_{\ell c}$ = squared long-crested RMS roll or variance

μ = predominant heading angle

σ^2_{sc} = squared short-crested RMS roll or variance.

The only interval required by the algorithm is I, the angular interval over which a constant wave energy-ship response is assumed.

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